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Terminal Airspace Decision Support Tools Preliminary Technical Performance Metrics and Economic Quantification

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Abstract

The Advanced Air Transportation Technologies (AATT) program of the National Aeronautics and Space Administration (NASA), in cooperation with the Federal Aviation Administration (FAA), is developing future improvements to the air traffic management (ATM) system. These research products include computer-based decision support tools (DSTs) designed to assist in the efficient planning and control of air traffic. The DSTs provide air traffic control (ATC) specialists and traffic management specialists with aircraft sequencing and scheduling plans, maneuver advisories, and related information pertinent to traffic and airspace supervision. Also, airline operations specialists are provided with air traffic status and prediction data. The AATT terminal airspace DSTs addressed are:

- Traffic Manager Advisor (TMA)
- Multi-Center (M-C) Traffic Manager Advisor
- Passive Final Approach Spacing Tool (pFAST)
- Active Approach Spacing Tool (aFAST)
- Collaborative Arrival Planning (CAP)
- Expedite Departure Path (EDP)

This study assesses DST potential impacts for a base year, 1996, and a future year, 2015. The analysis estimates the individual potential economic benefits of each DST with respect to impacts on aircraft operating costs, and identifies technical performance metrics applicable to the DSTs. The analysis is based on fast-time, computerized modelings of air traffic operations at ten selected study airport sites, the results of which are extrapolated to 33 other sites. The advanced Integrated Air Traffic Model (IAT) Model is used to simulate airspace and runway system operations at each study site for the current system and DSTs for 1996 and 2015 traffic loadings. The current system is used as a baseline for comparing DST potential impacts. The metrics pertain to ATM system performance indicators of capacity, flexibility, predictability, safety, access, and environment.

The IAT Model, newly developed by Seagull Technology, Inc., is a high-fidelity computerized simulation model specifically designed for quantitative evaluations of Free Flight and DST performance characteristics, as well as current operations. This advanced aircraft trajectory-based airport and airspace capacity and delay model enables representation of ATM operations and user preferences in constrained and unconstrained air traffic environments. The model simulates and evaluates DST impacts on aircraft operations with respect to flight delay, diversion, scheduling and planning. A set of computerized analytical routines is used to convert and extrapolate the minute-by-minute, hourly, or daily traffic delay metrics produced by the IAT Model to annual cost impacts. Cost estimation and extrapolation parameters include aircraft operating cost, annual traffic demand and meteorological factors.

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The study was led and conducted by Seagull Technology, Inc., Los Gatos, CA. Dr. George J. Couluris managed the project, and designed and directed the development and implementation of the Integrated Air Traffic (IAT) Model and benefits impacts analysis. Mr. David R. Schleicher performed the analysis of impacts on airline operations and supported the IAT Model development, testing and application. Ms. Tara Weidner supported the design and development of the IAT Model, particularly the runway system module and trajectory accuracy and spacing calibration. Mr. Richard Henthorn developed the IAT Model software system architecture and was the chief computer code development engineer. Mr. Carlos Gaudiamos structured and performed data organization, compilation and analysis efforts. Ms. Susan Dorsky provided software engineering support. Dr. Eric Miles prepared data reduction software code, and Mr. Lance Birtcil supported analysis of traffic data.

Technical and consultative support was provided by: Mr. Walter Faison of The Alaris Co., Incorporated, who developed airspace and runway system descriptions by airport, including arrival and departure routings, runway configurations and assignments, runway minimum spacing requirements and related modeling parameters; Roger Beatty of American Airlines System Operations Control (SOC) and Rose Shu of American Airlines, both of whom supported the assessment of potential impacts on airline operations; Dr. Robert Simpson and Ray Ausrotas of Flight Transportation Associates, Inc. (FTA) who contributed assessments of environmental impacts, and Mr. Larry Fortier of The Fortier Group, Inc., who provided consultative support regarding air traffic control operations and procedures.

Contents

List of Tables

List of Figures

Terminal Airspace Decision Support Tools Preliminary Technical Performance Metrics and Economic Quantification

Executive Summary

The National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) are cooperating in the research and development of future air traffic management (ATM) automation tools. NASA's Advanced Air Transportation Technologies (AATT) program is developing and enhancing computer-based decision support tools (DSTs). These products are designed to assist in the efficient planning and control of air traffic. The DSTs would provide air traffic control (ATC) specialists and traffic management specialists with aircraft sequencing and scheduling plans, maneuver advisories, and related information pertinent to traffic and airspace supervision. Also, DST's would provide air traffic status and prediction data to airline operations specialist.

This study analyzes the potential benefits of terminal airspace DSTs with respect to their impact on aircraft operating costs, and identifies performance metrics applicable to these DSTs. Ten selected airport sites are used as fast-time simulation modeling subjects to evaluate individual DSTs. The modeling exercises examine air traffic operations, DST performance, airspace and runway system throughput and delay, and aircraft operating cost relationships. The current ATM system is used as a basis for comparing DST potential impacts. The metrics pertain to ATM system performance indicators of capacity, flexibility, predictability, safety, access, and environment.

Terminal Airspace Decision Support Tools

The DST's addressed in this study are designed for implementation in the extended terminal airspace, which covers an area within approximately 250 nautical miles (nmi) of an airport. This domain includes airspace controlled by Terminal Radar Approach Control (TRACON) facilities and en route and transition airspace controlled by En Route Traffic Control Centers. These DSTs are:

- Traffic Manager Advisor (TMA)
- Multi-Center (M-C) Traffic Manager Advisor
- Passive Final Approach Spacing Tool (pFAST)
- Active Approach Spacing Tool (aFAST)
- Collaborative Arrival Planning (CAP)
- Expedite Departure Path (EDP)

The terminal airspace DSTs are part of and extensions of the Center-TRACON Automation System (CTAS). The CTAS computer software architecture includes generic modules which are common to DSTs, thereby effectively integrating DST operations. These software modules provide for communication, algorithmic, and graphical-user interface functions. The following summarize the terminal airspace DST operating characteristics

Traffic Manager Advisor (TMA) -- TMA automation supports Center operations by creating an optimum schedule for arrival aircraft crossing each metering fix, which is at the boundary between Center and TRACON airspace. TMA is designed to improve the flow of arrival traffic in the extended terminal airspace in compliance with air traffic rules restrictions. TMA predicts traffic throughput demand and develops aircraft schedules that minimize delay by planning the most efficient landing order. TMA assigns metering fix crossing times and landing times based on

runway system utilization and delay distribution optimization objectives. TMA implements sophisticated algorithms in real-time to synthesize very accurate cruise and descent trajectories based on high-fidelity aircraft performance models, wind aloft predictions, and flight plans.

Multi-Center Traffic Manager Advisor -- This tool extends TMA to enable integration of arrival traffic to an airport from multiple Centers. Without this capability, traffic manager coordinators in different Centers would have difficulty in tracking and visualizing all inbound traffic and mutually developing schedules to optimize runway utilization and delay distribution. This tool allows the implementation of TMA at a larger number of sites.

Passive Final Approach Spacing Tool (pFAST) -- pFAST automation supports TRACON operations by determining optimum landing sequence, schedule, and runway assignment advisories that balance runway use and maximize runway system throughput, and displaying runway assignment and schedule advisories to TRACON controllers. The algorithms very accurately predict 4-dimensional trajectories using detailed modeling of complex approach paths, flight plans, aircraft performance, user preferences and weather updates, and perform potential conflict detection and resolution.

Active Final Approach Spacing Tool (aFAST) -- aFAST automation extends the capabilities of pFAST by providing TRACON controllers with flight path maneuver advisories for each aircraft. aFAST displays speed and heading advisories with potential conflict detection and resolution capabilities that enable controllers to more accurately manage arrival aircraft trajectories and more-precisely control spacing.

Collaborative Arrival Planning (CAP) -- CAP automation supports the exchange of information between an airline facility and CTAS. This information exchange enables ATM to better accommodate user preferences in the scheduling and sequencing of arrival aircraft, and Airline Operations Center (AOC) and ramp management facilities to more accurately predict landings, terminal gate arrivals and hub connections and better plan the allocation of airline resources.

Expedite Departure Path (EDP) -- EDP automation extends TMA, pFAST, aFAST and CAP functionality to departure traffic, integrating arrival and departure DST operations. EDP will assist air traffic controllers in sequencing and spacing of departure traffic from airports and through adjoining airspace. EDP will enable controllers to predict and resolve conflicts more efficiently, meet traffic management and airspace constraints, and minimize deviations from user preferred trajectories. EDP will be based on accurate 4-dimensional trajectory prediction which accounts for aircraft performance, atmosphere, pilot-procedures, user-preferences and controller intent.

DST Operational Impacts

The AATT tools will enable improved aircraft trajectory control accuracy, improved knowledge of user preferences by ATM, and improved flight planning and scheduling flexibility by users. These improvements will increase ATM operational effectiveness relative to the current baseline operation and incrementally as tool implementations evolve. Operational improvements directly associated with AATT DSTs include:

- Reduced excess spacing between successive aircraft;
- More cost-effective distribution of delay between Center and TRACON airspace;
- Increased integration of ATM and user flight management operations, and increased accommodation of user preferences;
- Increased integration of arrival, departure and en route operations.

The potential benefits of these operational improvements include reduced aircraft direct operating costs, improved flight scheduling and planning, and enhanced safety, access, environmental factors, and controller and pilot productivity. The following paragraphs briefly review the operational improvements, focusing on the aircraft operating cost potential impacts which are relevant to the factors addressed in this study. Other benefits not covered would include passenger value of time savings, fuel savings due to improved aircraft trajectories, and productivity gains.

Excess Spacing Buffers

Actual spacings between aircraft, as implemented by air traffic controllers, are generally larger than the minimum separation requirements. Larger than minima separations have been observed for all types of traffic loadings, including periods of intense traffic activity. The observations of compacted traffic, where aircraft spacing is kept as small as possible by the ATM system, indicate that the extra spaces are not due simply to random interarrival characteristics of the traffic demand. These excess spacings are assumed to be intentional spacing buffers, which serve in part to assure that separation minima are not violated because of trajectory uncertainties.

Excess spacing is also generated by time uncertainty in the delivery of arrival aircraft at the inbound metering fixes. A schedule for the crossings of each fix is set by ATM. Deviations from the metering fix crossing schedule due to timing delivery inaccuracies require subsequent trajectory adjustments by the TRACON ATM operation to prevent violations of separation minima and, to the extent possible, eliminate extraneous gaps at downstream merge points and the runway threshold. The extraneous gaps may not be totally eliminated because aircraft are not always in position to allow corrective maneuvering within the TRACON airspace.

The reduction in trajectory uncertainty due to the DSTs relative to the current system would result in a reduction in the size of the excess spacing buffer needed to compensate for trajectory variances. The smaller buffer would reduce the spacing applied between successive aircraft, as set by the DST scheduling process. Improved trajectory accuracy also would reduce the propagation of extraneous gaps in the spacings actually realized. The resulting overall reduction in excess spacing would increase the throughput of the airspace and runway system. The increased throughput would reduce delays experienced by arrival aircraft when demand approaches or exceeds the capacity of the runway system, and would enable more efficient utilization of arrival routings and fixes. These reduced delays would result in reduced fuel and time costs incurred by aircraft operators. Departure traffic would also realize operating cost benefits through more efficient use of runway systems, departure routings and departure fixes.

Delay Distribution

TMA includes a delay distribution function which allocates aircraft delay between Center and TRACON airspace during busy traffic periods. The allocation process is designed to achieve an optimum balance between fuel burn savings and runway system throughput. The delay distribution function performs a trade-off between the advantage of absorbing delay at the higher en route altitudes, where fuel efficiency is greater, versus the advantage of packing more aircraft in the terminal airspace to ensure that aircraft are continually available to use the runway system. Excess allocation of delay to the Center airspace would degrade runway system utilization. As trajectory prediction and control accuracy is improved, less delay time is needed to be absorbed in the TRACON airspace to maintain high runway system throughput. However, in some cases the optimal TRACON delay that would minimize overall flight costs exceeds the delay absorption capabilities of the TRACON airspace. In these cases, the available TRACON delay absorption capability is best used to absorb metering fix delivery variability which would improve runway system throughput. Additionally, as no delay is shifted from the TRACON to the Center no incremental fuel savings are accrued by arriving aircraft.

The improved trajectory accuracy afforded by the DSTs would increase the proportion of delay that should be taken in the Center airspace for a given runway system throughput, providing additional cost savings due to the more fuel-efficient trajectories. These savings differ from those due to reduced excess spacings in that the excess spacings determine the runway system throughput and the associated amount of delay whereas delay distribution determines how the given amount of delay is taken.

ATM and User Preference Integration

The DSTs are designed to be sensitive and responsive to user preferences by accounting for user optimization objectives and allowing for real-time data exchange and collaborative decision making. The AATT terminal tools incorporate sophisticated logic that represent the performance characteristics of aircraft and propulsion systems and emulate flight management system (FMS) trajectory control characteristics. The DSTs' internal logic generate climb, descent and speed profiles, routings and schedules that are reasonably flight cost-efficient. Operating efficiency would further be enhanced through data exchange of user preferred trajectories (UPTs), aircraft capabilities and current and planned flight status, current meteorological measurements and forecasts, fleet prioritization information, schedule updates, and projected restrictions and delays. In future, the information exchange would be supported by data link among ATM, flight deck and AOC components. Future tool enhancements would adaptively assimilate the exchanged data to develop operating solutions that are compatible, to the extent possible, with user preferences. Collaborative decision making between ATM and users would further improve ATM conformance with user optimization objectives and allow users to adapt in real-time to ATM constraints.

Integrated Arrival, Departure And En Route Operations

The DSTs are designed to maximize air traffic operating efficiency in their airport and airspace coverage domain. The domain could be an extended terminal area with single or multiple airports supported by single or multiple en route centers, or a network of terminal areas and supporting centers. The DSTs will develop schedule and trajectory plans that optimize the arrival and departure operation at individual airports or among a network of airports in accordance with user preferences, operational constraints, and known or projected traffic and meteorological conditions. Factors addressed by the DSTs include runway balancing (i.e., optimal runway assignments to minimize delay), optimum aircraft sequencing, and satellite airport arrival and departures. These terminal operating plans would be developed in coordination with en route operations to provide safe and efficient utilization of airports and airspace and lessen disruptions to planned schedules and flight times. The result would be increased throughput, reduced delay, and better utilization of the air traffic system.

Other Factors

The overall ability of the AATT DSTs to implement more efficient trajectories, sequences and schedules with more accurate control would produce beneficial impacts on safety, access, noise and emissions, and controller and pilot productivity. Improved trajectory control and prediction would reduce the likelihood of airspace incursions and flight technical errors, and would facilitate interventions where needed. Improved throughput and scheduling would enhance general access to airports, airspace and air traffic services. The increased use of optimized trajectories with reduced delays would lessen noise exposure and the quantity of emitted pollutants. Automated advisories and plans generated by the tools would assist controllers and pilots in their decision making and implementation processes.

Analysis Process

A methodology incorporating analytical formulations, computer-based modeling and engineering analysis is used to evaluate DST performance and impacts on air traffic operations. The methodology examines improved aircraft trajectory control prediction and accuracy, improved knowledge of user preferences, and improved flight planning and scheduling flexibility, and determines the resulting impacts on aircraft operating costs and various performance metrics. The process focuses on capturing the salient operational features and nuances of the DSTs by modeling the purpose and intent of the DST algorithmic logic and accounting for procedural constraints and technical capabilities. This analysis process: identifies the operating characteristics of DSTs and supporting technologies; determines the sensitivity of various trajectory accuracy parameters to the use of the AATT DSTs and supporting technologies; evaluates the resulting improved capability of the ATM system to predict and control trajectories; evaluates delay, delay distribution, trajectory and scheduling impacts on flight operations using computer-based simulation modeling or engineering analysis; and assesses the associated aircraft operating cost savings and other pertinent metrics. Figure S-1 schematically depicts the generalized analysis process which uses simulation modeling to evaluate current system TMA, pFAST, aFAST and EDP. Engineering analysis is used to evaluate CAP impacts.

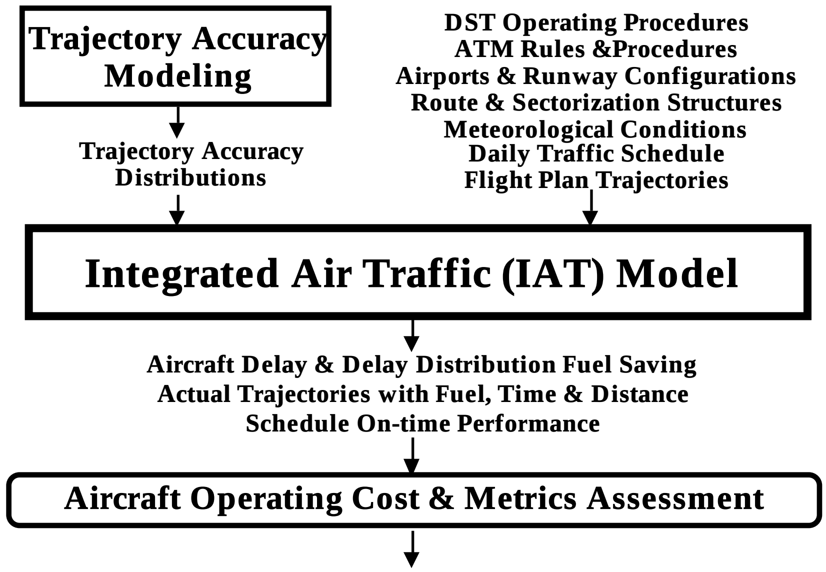


Figure S-1 Modeling Process

The following summarizes the analysis process steps:

Technologies and Capabilities Identification

The analysis process is initiated by identifying the subject DST and supporting technologies, and defining the associated operating capabilities in terms of functional, technical and performance characteristics and requirements. This process defines the airspace and runway system operating rules and procedures appropriate for the current system and DSTs, particularly those applicable to instrument and visual meteorological conditions at the subject airports.

Trajectory Accuracy and Traffic Spacing Modeling

Results of previous studies are used to relate trajectory accuracy and aircraft spacing characteristics for the current system and DSTs. The previous studies used the scheduled and actual crossings of metering fixes and runway threshold spacings observed during the CTAS prototype field tests to support a system of stochastic computer simulations and closed-form analytical solutions which model trajectory prediction and control accuracy. The modeling outputs are the excess spacing buffers applicable to runway system operations and the incremental fuel cost savings due to delay distribution optimization. These data are used to estimate trajectory variance and spacing buffer factors in the extended terminal airspace for current system and DST operations.

Runway System Demand and Capacity Model

A newly-developed fast-time computerized simulation, the Integrated Air Traffic (IAT) Model, is used to replicate the movement of individual aircraft through airport and airspace segments to assess capacity, delay, aircraft performance and operating cost relationships. The model processes data defining traffic demand, runway system configuration, airport and airspace operating procedures, and trajectory prediction and control accuracy, and examines DST impacts on aircraft operations with respect to flight delay, diversion, scheduling and planning. The IAT Model logic accounts for inter-aircraft spacings, and distinguishes the impacts on delay of the different trajectory control capabilities associated with the proposed tools as well as current operations. The model accounts for trajectory track, profile and schedule preferences, ATM trajectory sequence and schedule planning, runway assignment, potential conflict intervention, delay distribution, and stochastic effects.

Airspace and runway system throughput and delay are determined for each of the 10 study airports using the excess spacing buffer data and minimum separation requirements as input to the IAT Model. The model incorporates data describing time-varying daily flight schedules for 1996 and 2015 for various types of commercial, general aviation and military aircraft and detailed configurations of the subject airports for instrument flight rules (IFR) and visual flight rules (VFR). Modeling parameters describing separation procedures for the IFR and VFR runway configurations at each site are adjusted to enable comparison of current system and DST operations. The model provides daily traffic delay data by arrival and departure operations and instrument and visual meteorological conditions for the 10 airports under study for the current system and DSTs.

Aircraft Operating Cost Assessment

The daily traffic delay data are extrapolated to annual cost savings by airport using detailed aircraft direct operating costs, airport annual traffic forecasts and meteorological factors. Aircraft direct operating costs represent fuel, crew and maintenance costs expressed in 1996 undiscounted dollars.

Findings

Table S-1 summarizes the 1996 and 2015 estimated annual cost savings due to TMA, pFAST, aFAST and EDP for the 10 study airports, as derived from applications of the IAT Model. Table S-2 summarizes CAP annual cost savings estimates derived from engineering analysis.

The cost savings shown in Table S-1 are due delay reductions obtained from increased airspace and runway system throughput. The TMA data apply to Single and Multi-Center TMA sites for a 100-second delay TRACON airspace absorption limit. The 100-second limit is conservative in that it generally constrains TMA’s ability to improve the distribution of delay from TRACON to Center airspace relative to current operations. Greater TRACON delay absorption limits would enable TMA-based delay distribution optimization.

The quantitative analysis results support the functional expectations of DST potential benefits impacts as summarized below.

Single-Center and Multi-Center TMA contributes to more efficient runway system utilization by establishing optimized runway allocations and generating schedules and advisories for aircraft crossing the metering fix. Delay absorption advisories displayed to Center air traffic controllers are used to maneuver aircraft so that actual metering fix crossing times conform closely with the TMA schedule. An improved arrival time delivery accuracy at the metering fix relative to current operations is achieved, resulting in a reduction in the variance between the actual and predicted trajectories. More fuel efficient trajectories would be a direct result of TMA’s delay distribution function which diverts a proportion of flight delay from TRACON to Center airspace, reducing fuel burn without impacting runway system throughput and overall delay.

Table S-1 TMA, pFAST, aFAST and EDP Potential Annual Cost Savings Relative to the Current System

	Annual Aircraft Delay Cost Savings (1996 $ millions)							
	1996				2015			
Airport	TMA	pFAST	aFAST	EDP	TMA	pFAST	aFAST	EDP
DEN - Denver	5.48	0.41	0.76	6.83	8.44	1.39	1.90	12.23
DFW - Dallas-Ft. Worth	10.64	0.70	1.00	12.26	25.48	3.97	3.92	39.53
EWR - Newark [1]	5.95	3.91	4.13	12.96	7.87	41.76	56.16	92.34
JFK - N.Y. Kennedy [1]	3.72	4.09	5.87	10.08	5.35	7.01	9.68	15.77
LAX - Los Angeles	13.50	8.19	10.80	31.64	29.31	36.61	68.65	168.71
LGA - N.Y. LaGuardia [1]	8.00	1.15	1.28	9.17	13.01	16.54	10.47	23.54
MSP - Minneapolis	5.83	7.30	11.89	30.32	7.62	24.97	44.69	92.64
ORD - Chicago O'Hare	15.32	42.47	61.55	96.91	14.95	61.18	84.50	173.13
PHL - Philadelphia [1]	5.98	4.12	4.85	10.90	6.68	33.10	49.58	62.32
SFO - San Francisco	16.78	13.33	32.44	56.84	2.82	15.08	13.48	41.79
Total	91.21	85.66	134.57	277.92	121.52	241.62	343.02	722.00

1. Multi-Center TMA

Table S-2 CAP Potential Annual Cost Savings Relative to the Current System

	Nationwide Airline Savings ($millions/year)	
CAP Functionality	1996	2015
CTAS-to-Airline Data Exchange	>5.8	>9.0
Airline-to-CTAS Data Exchange	>48.2	>95.2
Intra-Airline Slot Swapping	Unknown, >0	Unknown, >0
TOTAL	50+	100+

pFAST determines efficient runway assignments, sequences and schedules for terminal area arrival aircraft, and displays the corresponding landing runway assignment and sequencing advisories to TRACON controllers. pFAST enables controllers to better utilize the runway and airspace system relative to current operations through reduced aircraft position uncertainty and improved runway balancing and aircraft trajectory sequencing. The improved controllability of spacing between successive aircraft effectively achieves a reduction in the excess spacing buffer. The pFAST runway balancing process increases system efficiency by assigning aircraft to the runway that minimizes overall delay. Improved trajectory sequencing integrates the terminal airspace arrival process with the runway system optimization plan, reinforcing the elimination of extraneous gaps at the runway so as to maintain a steady stream of landings.

aFAST enhances the pFAST runway assignment, sequencing, and scheduling functionality by displaying timely airspeed and heading advisories to controllers which are specifically directed to accurately positioning and spacing aircraft on terminal airspace arrival patterns, especially the final approach. Benefits derived from aFAST are analogous to those of pFAST, but with greater improvement impact. aFAST further reduces the variance between actual and planned aircraft position, reducing spacing buffer and extraneous gaps, and improves runway balancing and sequencing operations to reduce delay.

CAP provides airlines with timely updates of arrival time and terminal area delay predictions which allow for improved airline decision-making. Airlines can use the CAP information to improve ground personnel and equipment utilization, reduce baggage mishandling costs, reduce misconnections, reduce low-fuel diversions, and make better scheduling decisions. Additionally, CAP provides airline-sensed flight and weather information to CTAS to improve CTAS trajectory prediction accuracy. These trajectory prediction accuracy improvements will result in: reduced runway threshold spacing buffers which will lead to delay savings, better CTAS metering fix delivery accuracy which will lead to improved TRACON-Center delay distribution and more fuel efficient descent trajectories, and improved conflict detection accuracy which will lead to reduced ATM interruptions. Also, CAP provides decision support tools to support ATM and airline collaboration that will enable more airline control of arrival trajectories that will include concepts such as intra-airline slot swapping. These decision support tools will allow airlines to increase their control of flight arrival schedules and sequences, thereby enhancing schedule integrity, improving personnel and equipment utilization, and reducing inefficiencies such as misconnections and diversions.

EDP expands the functionality of TMA-FAST by including departures and multiple airport operations in the development of strategies to optimize traffic movement. The management of overtaking, crossing and merging situations involving arrivals and departures is improved by EDP-generated sequencing and spacing advisories which enable reduced spacing buffers. Runway system utilization is improved by simultaneously accounting for both arrival and departure traffic sequencing and spacing requirements. Improved trajectory control with EDP may enable controllers more frequently to approve expedited climbs with user-preferred speed and departure profiles. Integrated traffic planning by EDP would coordinate gate departure, runway takeoff and departure fix crossing scheduling to reduce ground and airspace delay and would facilitate the merging of satellite airport departures with the traffic flow of the major airport.

Conclusions

The following observations concerning TMA, pFAST, aFAST and EDP are made based on the modeling results obtained for the 10 study sites.

TMA improvements in trajectory prediction and control accuracy support <u>increased arrival airspace and runway system throughput</u> as a result of reduced spacing dispersions between aircraft pairs along en route arrival trajectories and at the metering fix relative to the current system. This improved metering fix delivery accuracy would also enhance the capability of CTAS-based ATM to <u>better distribute delay between Center and TRACON airspace.</u>

- The estimated aircraft operating cost savings associated with reduced arrival airspace and runway system delay due to TMA with a 100 second maximum TRACON delay absorption restriction, based on 1996 traffic forecasts, range from $3.72 to 16.78 million annually for the 10 study sites and $2.82 to 29.31 million annually for the 2015 traffic forecasts.
- Total estimated TMA delay savings benefits for all 10 sites are $91.21 million and $121.52 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total TMA delay savings benefits in respective order of magnitude are SFO, ORD and LAX in 1996, and LAX, DFW, and ORD 2015.
- When TRACON delay absorption is unrestricted, aircraft would consume a greater proportion of their delay in the more fuel-efficient Center airspace rather than the TRACON airspace without impacting runway throughput and total delay. Otherwise, the available TRACON delay absorption capability would be best used to absorb metering fix delivery variability in order to maximize runway system throughput.
- TMA estimated incremental aircraft fuel cost savings due to delay distribution at all 10 airports under study with a 100 second maximum TRACON delay absorption restriction are zero.

- Based on previous study results, TMA estimated incremental aircraft fuel cost savings due to delay distribution with a 200 second maximum TRACON delay absorption restriction, could be at least 10% of the savings due to reduced runway system delay.

pFAST improvements in arrival trajectory prediction and control accuracy in association with improved arrival sequencing and runway assignment enable reductions in excess spacing buffers between aircraft pairs along terminal area arrival trajectories and at runway thresholds relative to the current system. The resulting increases in arrival airspace and runway system throughput generates reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced arrival airspace and runway system delay due to pFAST at 10 airports under study range from $0.41 to 42.47 million annually based on 1996 traffic forecasts and $1.39 to 61.18 million annually based on 2015 traffic forecasts.
- Total estimated pFAST benefits for all 10 sites are $85.66 million and $241.62 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total pFAST delay savings benefits in respective order of magnitude are ORD, SFO and LAX in 1996, and ORD, EWR and LAX in 2015.

aFAST improvements in arrival trajectory prediction and control accuracy in association with improved arrival sequencing and runway assignment enable further reductions in excess spacing buffers between aircraft pairs along terminal area arrival trajectories and at runway thresholds relative to the current system. The resulting increases in arrival airspace and runway system throughput generates further reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced arrival airspace and runway system delay due to aFAST at 10 airports under study range from $0.76 to 61.55 million annually based on 1996 traffic forecasts and $1.9 to 84.5 million annually based on 2015 traffic forecasts.
- Total estimated aFAST benefits for all 10 sites are $134.57 million and $343.02 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total aFAST delay savings benefits in respective order of magnitude are ORD, SFO and MSP in 1996, and ORD, LAX and EWR in 2015.

EDP improvements in departure trajectory prediction and control accuracy in association with improved arrival and departure sequencing and runway assignment enable reductions in excess spacing buffers between aircraft pairs along en route and terminal area departure trajectories and at runway thresholds relative to the current system. The resulting increases in departure and arrival airspace and runway system throughput generates further reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced departure and arrival airspace and runway system delay due to EDP at 10 airports under study range from $6.83 to 96.91 million annually based on 1996 traffic forecasts and $12.23 to 173.13 million annually based on 2015 traffic forecasts.
- Total estimated EDP benefits for all 10 sites are $277.92 million and $722 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total EDP delay savings benefits in respective order of magnitude are ORD, SFO and LAX in 1996, and ORD, LAX and EWR 2015.

The modeling of current and DST operations develops a runway utilization schedule and assignment plan assuming knowledge of the exact sequence of actual departures. In fact, the current system does not have such specific pre-takeoff data defining the actual departure traffic. TMA, pFAST and aFAST process data for arrival operations, but could be enhanced with pre-takeoff departure traffic data subject to system design and implementation. Because EDP integrates arrival and departure planning, the benefits of EDP may be understated relative to current operations and, depending on implementation, the other DSTs.

The pFAST, aFAST and EDP delay savings are highly sensitive to the IMC and VMC runway system configurations assumed at each airport.

The following observations concerning CAP are made based on engineering analysis results.

A conservative estimate of the potential benefits of CAP for 43 airports in this study results in a rough-order-of-magnitude estimate of $50 million per year for 1996 and $100 millions per year for 2015. In general, the preliminary benefits associated with Airline-to-CTAS data exchanges tend to be significantly higher than those associated with CTAS-to-Airline data exchanges:

- Airline-to-CTAS estimated annual savings are $48.2 million and $95.2 million in 1996 and 2015 respectively.
- CTAS-to-Airline estimated annual savings are $5.8 million and $9 million in 1996 and 2015 respectively.

The lower CTAS-to-Airline data exchange benefits would be due to the tendency for CTAS-to-Airline data exchanges to provide significant economic benefits during off-nominal events such as low-fuel diversions or baggage misconnections. In the case of Airline-to-CTAS data exchange, the benefits are much smaller per event, but these nominal events are of very high frequency and result in higher total economic values.

Analysis Considerations and Recommendations

This study uses a new, advanced modeling capability, the Integrated Air Traffic Model, to evaluate potential aircraft operating cost savings due to the implementation of terminal airspace DSTs. The IAT Model currently evaluates traffic loading, capacity and delay characteristics of operations in the extended terminal airspace and runway system associated with a single study airport.

The IAT Model is undergoing initial development, and is subject to review and verification. Various useful expansions to the analytical scope of the IAT Model were evident during its application in this study. The model structure is extendible to realistically emulate multi-airport regional operations such as the US Northeast Corridor and other high-density domains. The value of this extension is exemplified by the individual analysis in this study of a subset of airports (i.e., JFK, LGA, EWR, and PHL) which share common arrival and departure fixes. This multi-airport network modeling function would include the capability to evaluate of satellite airport operations Also, the development of a airport network-based IAT Model could be directed to nationwide coverage.

The current IAT Model examines airspace trajectory and runway system operations, incorporating the salient capabilities of the trajectory accuracy and standard runway utilization modeling. The trajectory component tracks and optimizes scheduling, sequencing and spacing factors at discrete fixes. A logical extension in scope is the incorporation of continuous trajectory modeling to capture in more detail the operational dynamics associated with conflict detection and resolution maneuvers.

The limited time available to perform this study precluded extensive data sampling and collection, field experimentation, on-site observation and consultation, modeling and related investigations for each site. Many assumptions were necessary to develop preliminary estimates of potential benefits. An expansion of the scope and depth of the data collection and analysis procedures would facilitate a broad representation of and participation by the aviation community and lessen the dependence on analytical assumptions and extrapolations.

Terminal Airspace Decision Support Tools Preliminary Technical Performance Metrics and Economic Quantification

1. Introduction

Research programs by the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA) and the aviation industry are developing new technologies for improving future air traffic operations. [ref.1] As part of these coordinated efforts, NASA's Advanced Air Transportation Technologies (AATT) program is supporting the evolution of the National Airspace System (NAS) toward the implementation of the Free Flight concept. [ref.2] Free Flight provides for increased user flexibility, with improved operating efficiencies and increased levels of capacity and safety to meet growing demand. Free Flight would achieve significant benefits by removing constraints and restrictions to flight operations, providing better exchange of information and collaborative decision making among users and service providers, implementing more efficient management of airspace and airport resources, and developing and applying tools and models to aid air traffic management (ATM) operations. [ref.3]

The AATT program is developing system enhancements for incorporation into future Free Fight operations [ref.3,4]. These AATT research products currently are primarily ATM <u>decision support tools</u> (DSTs). The DSTs are computer-based automation functions designed to assist in the efficient planning and control of air traffic. The DSTs would provide air traffic control (ATC) specialists and traffic management specialists with aircraft sequencing and scheduling plans, maneuver advisories, and related information pertinent to traffic and airspace supervision. Also, DST's would provide air traffic status and prediction data to airline operations specialist.

The AATT program will develop these products to a state suitable for pre-production prototype development by the FAA and industry, leading eventually to full-scale development and deployment. This Concept Exploration and Concept Development process is consistent with an ATM Concept of Operations, [ref.2] defined by the AATT program for use as a guide in determining its research directions and development activities. This ATM Concept integrates joint government and industry NAS operational concepts, [ref.5] and describes an incremental evolution of the NAS from current operations to a mature state, nominally, the year 2015, which provides advanced Free Flight capabilities.

The AATT program is in an early phase, with planning options and flexible priorities. The DSTs are in various stages of development, ranging from concept development to prototype demonstration. Some of the earlier tools are in initial deployment. Given the various levels of maturity of the tools and the ability to leverage or direct technical emphasis to improve the performance of various tools, an evaluation of the potential impacts of the DSTs would provide useful insight into the operational advantages obtainable with each tool.

NASA's AATT program is initiating potential benefit assessments of DSTs planned for terminal airspace, terminal surface, en route and airborne operations. As part of this effort, the study described in this report addresses potential benefits impacts of terminal airspace DSTs. The AATT terminal airspace DSTs addressed are:

- Traffic Manager Advisor (TMA)
- Multi-Center (M-C) Traffic Manager Advisor
- Passive Final Approach Spacing Tool (pFAST)
- Active Approach Spacing Tool (aFAST)
- Collaborative Arrival Planning (CAP)

- Expedite Departure Path (EDP)

This study assesses DST potential impacts for a base year, 1996, and a future year, 2015. The analysis estimates the individual potential economic benefits of each DST with respect to impacts on aircraft operating costs, and identifies technical performance metrics applicable to the DSTs. The analysis is based on modelings of air traffic operations at ten selected study airport sites, the results of which are extrapolated to 33 other sites. The modelings are fast-time computer simulations of airspace and runway system operations at each study site for the current system and DSTs for 1996 and 2015 traffic loadings. The current system is used as a baseline for comparing DST potential impacts. The metrics pertain to ATM system performance indicators of capacity, flexibility, predictability, safety, access, and environment.

Terminal Airspace Decision Support Tools

The DST's subjects of this study are designed for implementation in the extended terminal airspace which covers an area within approximately 250 nautical miles (nmi) of an airport. This domain includes airspace controlled by Terminal Radar Approach Control (TRACON) facilities and en route and transition airspace controlled by En Route Traffic Control Centers (ARTCCs). The potential operational characteristics and impacts of these terminal airspace DSTs are summarized in the following paragraphs.

Traffic Manager Advisor (TMA) -- TMA automation creates an optimum schedule for arrival aircraft crossing each metering fix, which is at the boundary between Center and TRACON airspace. TMA is designed to improve the flow of arrival traffic in the extended terminal airspace in compliance with air traffic rules restrictions. TMA predicts traffic throughput demand and develops aircraft schedules that minimize delay by planning the most efficient landing order. TMA assigns metering fix crossing times and landing times based on runway system utilization and delay distribution optimization objectives. TMA implements sophisticated algorithms in real-time to synthesize very accurate cruise and descent trajectories based on high-fidelity aircraft performance models, wind aloft predictions, and flight plans. TMA would reduce delays to aircraft, especially during rush periods at hub airports, and facilitate more fuel-efficient trajectories.[ref.1]

Multi-Center Traffic Manager Advisor -- This tool extends TMA to enable integration of arrival traffic to an airport from multiple ARTCCs. Without this capability, traffic manager coordinators in different Centers would have difficulty in tracking and visualizing all inbound traffic and mutually developing schedules to optimize runway utilization and delay distribution. This tool allows the implementation of TMA at a larger number of sites, further facilitating reduced delays and improved trajectories.

Passive Final Approach Spacing Tool (pFAST) -- pFAST automation determines optimum landing sequence, schedule, and runway assignment advisories that balance runway use, maximize runway system throughput, and display runway assignment and schedule advisories to TRACON controllers. The algorithms very accurately predict 4-dimensional trajectories using detailed modeling of complex approach paths, flight plans, aircraft performance, user preferences and weather updates, and perform potential conflict detection and resolution. pFAST would reduce air traffic delay and controller workload and improve safety through improved controller situation awareness for varying demand levels, meteorological conditions, and runway configurations.[ref.1]

Active Final Approach Spacing Tool (aFAST) -- aFAST automation extends the capabilities of pFAST by providing controllers with flight path maneuver advisories for each aircraft. aFAST displays speed and heading advisories with potential conflict detection and resolution capabilities that enable controllers to more accurately manage arrival aircraft trajectories and more-precisely control spacing The resulting reduction in excess gaps between aircraft will increase airport and airspace throughput. pFAST would reduce air traffic delay and controller cognitive workload.[ref.1]

Collaborative Arrival Planning (CAP) -- CAP automation supports the exchange of information between an airline facility and CTAS. This information exchange enables ATM to better accommodate user preferences in the scheduling and sequencing of arrival aircraft, and Airline Operations Center (AOC) and ramp management facilities to more accurately predict landings, terminal gate arrivals and hub connections and better plan the allocation of airline resources. CAP would enhance ATM and user flexibility, reducing delays due to disruptions to scheduled operations. [ref.1]

Expedite Departure Path (EDP) -- EDP automation extends TMA, pFAST, aFAST and CAP functionality to departure operations. EDP will assist air traffic controllers in sequencing and spacing of departure traffic from airports and through adjoining airspace. EDP will enable controllers to predict and resolve conflicts more efficiently, meet traffic management and airspace constraints, and minimize deviations from user preferred trajectories. EDP will be based on accurate 4-dimensional trajectory prediction which accounts for aircraft performance, atmosphere, pilot-procedures, user-preferences and controller intent. EDP would reduce air traffic delay and facilitate more fuel-efficient trajectories.

Center-TRACON Automation System Software Processes

The terminal airspace DSTs are part of and extensions of the Center-TRACON Automation System (CTAS). The current CTAS computer software architecture includes generic modules which are common to DSTs, thereby effectively integrating DST operations. These software modules provide for communication, algorithmic, and graphical-user interface functions as described below. [ref.6-11]

Communications Modules

The communications modules manage CTAS internal message routing and the data exchange interfaces with external systems. These support CTAS computer message transactions with Center and TRACON automation and CTAS acquisition of flight, radar and weather data. Information processed include: flight plans describing aircraft type, flight route, cruise altitude and speed, and take-off time; radar tracking data describing aircraft position, altitude and speed; controller-entered flight plan amendments and deletions; controller-entered CTAS commands; DST-generated traffic planning data and advisories; and weather data products from the National Weather Service (NWS) or elsewhere. The National Oceanic and Atmospheric Administration (NOAA) Rapid-Update Cycle (RUC) computational process provides gridded weather nowcasts approximately every three hours. The major communications modules are:

Communications Manager (CM) -- CM controls internal data distribution and external data interface functions.

Data Acquisition and Distribution System (DADS) -- DADS provides communications with TRACON computer systems.

Host Data Acquisition and Routing (HDAR) -- HDAR provides communications with a Center's Host computer system.

Input Source Manager (ISM) -- ISM assembles, transforms, filters and merges data received from external systems.

Weather Data Acquisition Daemon -- WDPA collects weather data inputs.

Algorithmic Modules

The algorithmic modules perform analysis, prediction and solution processes for the DSTs. The major modules are:

Route Analyzer (RA) -- RA generates feasible horizontal route alternatives for an aircraft from its current position to an end point such as the destination runway threshold. RA analyzes data describing aircraft state and engine type; aircraft flight plan and radar track (i.e., position, altitude, ground speed and time), airport runway configuration and eligible runways; and route and speed degree of freedom parameters defining permissible path stretching maneuvers, speed change range and location, and turn points. RA specifies aircraft state (i.e., position, altitude, heading and speed), waypoint, endpoint and applicable degree of freedom data for each route.

Trajectory Synthesizer (TS) -- TS generates high-fidelity 4-dimensional trajectories and corresponding expected time of arrival (ETA) data for a specified horizontal route. ETAs represent flight time unaffected by air traffic considerations. TS analyzes aircraft model data (i.e., aircraft aerodynamics, propulsion characteristics and preferred speeds), atmospheric data (i.e., winds aloft, air temperature and pressure profiles), aircraft initial status, waypoints, desired end conditions (i.e., altitude, airspeed and location), and intermediate altitude and speed constraints. TS constructs a time-defined vertical profile along a smooth horizontal path, including turns, based on the waypoints, resulting in time-to-fly estimates. TS can compute nominal, fast and slow flight times, and can generate trajectories to satisfy a required time of arrival (RTA).

The Route Analyzer and Trajectory Synthesizer modules are fundamental elements of the CTAS tools, and are designed for synergetic operation. The Route Analyzer can use the Trajectory Synthesizer to define an optimal flight trajectory with ETAs.

Dynamic Planner (DP) -- DP supports TMA by scheduling airport arrivals. DP analyzes flight plan and Center radar track data, route specifications and ETAs to eligible runways provided by the Route Analyzer/Trajectory Synthesizer modules, and airport scheduling and runway utilization rules. DP determines runway assignment and the aircraft sequence and scheduled time of arrival (STA) at the outer metering arc (e.g., 250 radius) , metering fix, final approach fix, and runway thresholds for each aircraft.

Profile Selector (PFS) -- PFS supports arrival operations of pFAST and aFAST. PFS generates aircraft runway assignments and sequence and schedule assignments along flight paths such that aircraft maintain proper spacing and avoid potential conflicts (i.e., avoid violation of minimum separation requirements). PFS analyzes data describing flight plans, Center and TRACON radar tracks, and route specifications generated by the Route Analyzer module. PFS uses data generated by the Trajectory Synthesizer to determine aircraft ordering and spacing, identify potential conflicts, examine resolutions, and define sequence and schedule plans.

Profile Selector - Center (PFS_C) -- PFS_C supports en route tools such as En Route and Descent Advisor (EDA) and User Preferred Routing (UPR), and is analogous to Profile Selector. PFS_C analyzes flight plan and track data, specifications generated by the Route Analyzer module, and STA’s generated by the Dynamic Planner module. Using data generated by the Trajectory Synthesizer, PFS_C performs conflict probing, resolves trajectories and determines ETAs.

Weather-Data Processing Daemon (WDPD) -- WDPD converts weather data collected by the Weather Data Acquisition Daemon module into files usable by other modules.

Graphical-User Interface Modules

The major graphical-user interface modules are:

Planview Graphical User Interface (PGUI) -- The PGUI displays a plan view of the traffic situation, delay absorption advisories, lists and timelines, and receives input from controllers or coordinators.

Timeline Graphical User Interface (TGUI) -- TGUI displays timeline, load graph and textual data, and receives input from coordinators.

Sections 2 through 7 of this report describe each terminal airspace DSTs in further detail using information assembled, interpreted or directly extracted from reference 1 and references 6 through 12. Section 8 reviews potential benefits analysis considerations and identifies candidate performance metrics. Section 9 describes the airspace and runway system modeling process, its application, and results. Section 10 describes additional engineering analysis as applied to airline and environmental impacts. Section 10 presents conclusions and recommendations.

2. Traffic Manager Advisor

TMA develops a sequencing and scheduling plan for arrival aircraft to an airport that directly supports Center operations, but is based on optimizing runway system and extended terminal airspace operations. TMA aids Center air traffic controllers and traffic management coordinators in the establishment of efficient inbound traffic flows and distributions and in the timely delivery of aircraft to metering fixes at the Center-TRACON boundary.

The TMA system evaluates a variety of parameters to perform its automation function. TMA generates undelayed ETAs for all aircraft at the outer metering arc, metering fix, final approach fix and arrival threshold of each eligible runway in the current airport configuration. TMA computes the sequences and STAs for all aircraft at the outer metering arc, metering fix, final approach fix and threshold. Minimum separation requirements are applied to STAs at the metering fix, final approach fix and threshold. In conjunction with the sequencing and scheduling process, TMA determines a runway assignment for each aircraft based on runway system delay reduction optimization logic and adjusts an aircraft’s schedule to optimize delay distribution between TRACON and Center airspace.

TMA displays graphical timeline, load chart, planview traffic situation and linear list data to Center traffic management coordinators, and displays aircraft schedule crossing and delay absorption advisories to Center sector controllers. Traffic management coordinators may enter data to manually adjust sequence, schedule and runway assignments and processing parameters. TMA data can be transmitted for display at TRACON and ATC towers sites. Timeline and related data are also used by TRACON traffic managers to plan and coordinate inbound flows.

TMA System Operation

TMA continually updates its results using radar and flight data from the Center computer system in responding to changing events and controller and coordinator inputs. TMA performs sequencing and scheduling for aircraft in the Center's airspace (approximately 40 to 200 miles from the arrival airport) and schedules some aircraft before entering the Center's airspace provided the flight plan is received. The scheduling updates continue until an aircraft's metering fix ETA is less than or equal to 19 minutes in the future (the “freeze horizon”), at which point the aircraft's STA is frozen. The TMA-generated STAs and runway assignments may be overruled by FAST when aircraft enter the TRACON airspace.

TMA sequences aircraft according to ETAs at the metering fix using first-come first served ordering with adjustments within each super stream class. Aircraft in each such class share common characteristics, such as engine type (i.e., turbojet, turboprop or piston), destination airport and metering fix.

Metering fix STAs are calculated after the metering fix sequence is determined for each aircraft. An aircraft’s STA may only be set equal to or later than its metering fix nominal ETA, based on scheduling constraints and sequence position. An STA later than the aircraft’s ETA signifies delay in the en route airspace upstream of the metering fix. Metering fix scheduling constraints are:

- TRACON Acceptance Rate: the maximum number of aircraft per hour that can be scheduled to enter the TRACON airspace.
- Meter Fix Acceptance Rate: the maximum number of aircraft per hour that can be scheduled to cross a meter fix; each meter fix has its own meter fix acceptance rate.
- Gate Acceptance Rate: the maximum number of aircraft per hour that can be scheduled to cross any of the meter fixes contained within a gate; each gate has its own gate acceptance rate.
- Super Stream Class Miles-In-Trail Separation: the separation, in nautical miles, between aircraft as they cross the meter fix; each super stream class has its own miles-in-trail restriction.

- Meter Fix Blocked Intervals: time intervals during which aircraft may not be scheduled to cross the meter fix.

Runway STAs then are determined based on consideration of the preliminary metering fix STAs and runway ETAs, subject to scheduling constraints. The TRACON transition time (i.e., the difference between metering fix and runway ETAs) is calculated for each aircraft, and any TMA-planned delay in the TRACON airspace due to scheduling constraints is determined. Runway scheduling constraints are:

- Airport Acceptance Rate: the maximum number of aircraft per hour that can be scheduled to land at a particular airport.
- Runway Acceptance Rate: the maximum number of aircraft per hour that can be scheduled to land on a particular runway.
- Wake Vortex Separation: minimum separation requirement, in nautical miles, between aircraft as they land; the amount of separation varies depending on the engine type and weight class of the two aircraft to be separated from each other.
- Runway Occupancy Time: the additional time between arriving aircraft to account for various stopping conditions and the amount of time required by a landed aircraft to clear the runway.
- Runway Blocked Intervals: the time intervals during which aircraft may not be scheduled to land.

TMA applies the runway scheduling constraints at the arrival threshold for instrument flight rule (IFR) operations and at the final approach fix for visual flight rule (VFR) operations.

TMA exercises its delay distribution function to govern the delay planned for absorption in the TRACON airspace according to a preset limit for that TRACON. The STAs are adjusted to reallocate delay between TRACON and Center airspace.

TMA then computes the STAs at the outer metering arc given the metering fix and runway ETAs and STAs for all aircraft. TMA does not apply scheduling constraints at the outer metering arc, and remaining differences among and between STAs and ETAs are absorbed as planned delay within the TMA Center airspace.

TMA invokes a runway allocation process designed to reduce overall runway system delay. The process examines ETAs to all eligible runways for new arrivals to define initial runway assignments and STAs that would have the best runway acceptance rate result. During the subsequent scheduling processes for aircraft transiting the Center airspace, TMA continuously responds to traffic events and evaluates runway reassignment options. TMA considers the aircraft’s destination airport and runway configuration, assigned metering fix and aircraft engine type; develops and evaluates trial runway assignments and STAs; and searches for the scheduling and runway assignment solution with the best impact on STA-defined system delay.

TMA Potential Benefits

In addition to serving as a coordination and planning tool for traffic managers, TMA provides a capability to reduce flight operating costs and noxious emissions. These benefits are derived from reduced delays due to more efficient runway utilization and more fuel-efficient distribution of delay between Center and TRACON airspace.

TMA contributes to more efficient runway system utilization by establishing expedient runway allocations and generating schedules and advisories for aircraft crossing the metering fix. Delay absorption advisories displayed to Center air traffic controllers are used to maneuver aircraft so that actual metering fix crossing times conform closely with the TMA schedule. An improved arrival time delivery accuracy at the metering fix relative to current operations is achieved, resulting in a reduction in the variance between the actual and predicted trajectories.

More fuel efficient trajectories are a direct result of TMA's delay distribution function which diverts a proportion of flight delay from TRACON to Center airspace, reducing fuel burn without impacting runway system throughput and overall delay.

TMA automation is able to establish an efficient airspace and runway system utilization plan and implement the plan more effectively than could current manual ATM operations. The TMA benefits mechanisms are further explained in the following paragraphs.

TMA Delay Reduction

Actual spacings between aircraft, as implemented by air traffic controllers, must meet minimum separation requirements. Minimum separation requirements are formally specified by the Federal Aviation Administration.[ref.13] Observations[ref.14] of terminal operations during busy traffic conditions, when traffic is compressed and runway throughput is high, indicate that actual spacings between successive aircraft exceed the minimum longitudinal separation requirement by some small amount. These excess spacing buffers serve in part to assure that separation minima are not violated because of trajectory uncertainties. The excess spacing buffer provides an allowance for the variance between actual and predicted trajectories, precluding the situation in which variations from the intended longitudinal positions of successive aircraft would cause their closure distance to be less than a minimum separation requirement.

Quite apart from the process of maintaining proper pairwise separation between successive aircraft, time uncertainty in the delivery of aircraft at a fix also contributes to excess spacing. In the extended terminal airspace, arrival aircraft cross different inbound metering fixes. Current ATM operations develop an aircraft crossing schedule for each metering fix using time or distance-based traffic flow methods. The TMA sets either a time-based or miles-in-trail schedule for the crossings of each fix. The TMA schedule is an improvement over the current system schedule as TMA uses highly accurate trajectory prediction models and incorporates an aircraft-by-aircraft sequencing plan for downstream merging in the TRACON airspace and runway landings. However, as with any system, prediction and control inaccuracy causes deviations from a metering fix crossing schedule. The deviations require subsequent trajectory adjustments by the downstream TRACON controllers to prevent violations of separation minima and, to the extent possible, eliminate extraneous gaps at downstream merge points and the runway threshold. The extraneous gaps may not be totally eliminated because aircraft are not always in position to allow corrective maneuvering within the TRACON airspace. These extraneous gaps may be referred to as "missed slots" in that they represent missed opportunities to fit additional traffic into the approach patterns. The resulting contribution to the excess spacing is directly related to the variance between the actual and predicted crossing of the metering fix as observed in recent field tests[ref.15,16] at Dallas-Fort Worth International Airport (DFW).

TMA Delay Distribution

Improved trajectory accuracy would also impact the fuel burn efficiency associated with the distribution of arrival flight delay between the TRACON and Center airspaces. Given a specified amount of delay, part of the delay would be absorbed in the lower terminal altitudes to maintain efficient runway utilization, as follows. Scheduling some delay in the terminal airspace allows TRACON controllers more flexibility to absorb the metering fix crossing variability, allowing them to increase runway system utilization. Thus, late arrivals at the metering fix can be maneuvered so to forgo this scheduled delay and reach the runway earlier, mitigating extraneous gaps. Without this scheduled delay, late aircraft at the metering fix would also be late at the runway threshold, thus maintaining extraneous gaps in the arrival stream which reduce the airport arrival throughput an increase delay. The remainder of the overall delay is absorbed at higher en route altitudes, where the fuel burn is more efficient.

TMA implements a delay distribution function which optimizes the allocation of delay between Center and TRACON airspaces. The function is sensitive to metering fix delivery accuracy because a significant improvement in metering fix accuracy enables built-in TRACON delay meant to absorb trajectory variations to be shifted to Center airspace where it can be absorbed with greater fuel efficiency. In this way, the same amount of delay is absorbed more efficiently, resulting in a net fuel savings.

Delay Reduction and Distribution Interaction

Improved metering fix accuracy has two interrelated effects that are leveraged by TMA:

- runway utilization is improved and delay is decreased due to a reduction in the extraneous gap contribution to the excess spacing buffer
- fuel burn is reduced by incrementally allocating a larger proportion of the planned delay to Center airspace.

The interaction is due to the cost trade-off that exists between high runway utilization (reduced extraneous gap delay costs) and delay distribution incremental fuel costs associated with higher TRACON fuel burn rates. As a result of the trade-off, an optimum exists.

Figure 1-1 represents this relationship for two metering fix accuracy levels (σ_{MF}). For explanatory analysis purposes, this representation employs an ideal TRACON Delay Setting (amount of built-in TRACON delay) that will minimize combined costs of delay and fuel. As shown, the optimum or minimum cost TRACON Delay Setting differs for the two bold total cost curves, derived from the two metering fix accuracy levels of 100 and 45 sec. The plot shows that improved metering fix accuracy optimally leads to reduced built-in TRACON delay (158 to 71 seconds), with savings in both delay distribution incremental fuel cost (ΔFuel) and extraneous gap/missed landing slot delay. In the event that the TRACON Delay Setting were held fixed while metering fix accuracy improved (vertical slide between total cost curves) the system would be expected to experience significant delay savings (vertical difference between delay curves) without any savings in delay distribution incremental fuel costs (ΔFuel curve does not change). Overall, this results in a suboptimal improvement in total costs.

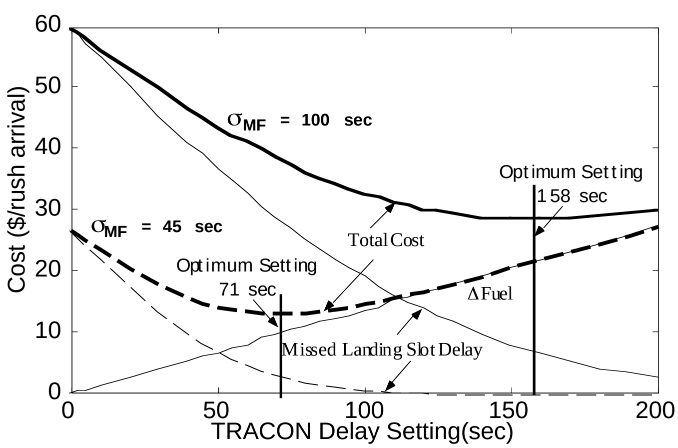


Figure 1-1 Extraneous Gap and Delay Distribution Incremental Fuel Cost Tradeoff

However, based on previous studies of TRACON flight track data, [ref.17,18] terminal airspace can typically only absorb 100 to 200 seconds of delay on average beyond the fastest feasible path to the runway. The maximum delay that can realistically be accommodated in the TRACON airspace is constrained by the airspace geometry and complexity of air traffic control operations. Facilities can occasionally handle higher amounts of delay but would be overburdened if most aircraft required such attention. If we restrict the TRACON Delay Setting accordingly, the results change considerably. At high metering fix delivery accuracies, when the Delay Setting is bounded by this restriction, large extraneous gap delay saving but no delay distribution incremental fuel saving are expected to result from metering fix accuracy improvements. In this case, all the available TRACON delay absorption capability is best used to absorb metering fix delivery variability in order to reduce extraneous gap delay, thereby increasing runway system throughput. This occurs until the accuracy improves to the point that the optimal Delay Setting is no longer constrained by the available TRACON absorption capability. That is, although the metering fix delivery accuracy improves, no delay is shifted from TRACON to Center airspace until the system operates optimally. Once the optimal delay setting is no longer bound by the restriction, both extraneous gap delay savings and delay distribution incremental fuel savings will occur.

A previous study [ref.15] analyzed the delay distribution incremental fuel savings and extraneous gap delay contribution to the spacing buffer using metering fix delivery accuracy obtained from TMA prototype field tests at DFW. The field tests provided data describing actual and TMA-planned aircraft crossings of the metering fix during current system and TMA operations. Table 2-1 presents these theoretically-derived values for two TRACON Delay Setting values: 100 and 200 seconds.

Table 2-1 TMA TRACON Delay Setting Comparison

	Observed Metering Fix Delivery Accuracy	TRACON Delay Setting		Threshold Excess Spacing Buffer Extraneous Gap Delay Contribution(μ_{MS})	Delay Distribution Incremental Fuel Cost
		Optimal	Max Setting		
Current System	180 sec	284 sec	100 sec	3.57 sec	$12.88/ac
CTAS TMA System	90 sec	142 sec	100 sec	0.82 sec	$12.88/ac
Current System	180 sec	284 sec	200 sec	1.65 sec	$25.76/ac
CTAS TMA System	90 sec	142 sec	200 sec	0.35 sec	$18.31/ac

The second column presents metering fix delivery accuracies determined from the field test results. The third column identifies the derived optimal TRACON Delay Setting, while the next column identifies the restricted maximum setting. This maximum setting defines the limit on a TRACON's ability to absorb delay beyond the least time to fly. The table shading indicates which of the two settings, 100 or 200 seconds, is limiting. The fifth column identifies the extraneous gap delay contribution to the threshold excess spacing buffer. The final column in the table identifies the average fuel cost (using the DFW fleet mix) per arriving aircraft associated with absorbing delay in the TRACON above the fastest path. Its value depends on the chosen TRACON Delay Setting.

Relative to the Current System, TMA with either the 100 or 200 second setting reduces the threshold excess spacing buffer contribution because the extraneous gap delay on final is reduced with improved metering fix crossing accuracy. A larger spacing buffer reduction is found with the more restrictive 100 second maximum TRACON delay absorption threshold. This occurs because insufficient delay slack is available in the TRACON airspace with the limited setting to absorb the system's metering fix variability, significantly increasing the extraneous gap contribution to the buffer. With a 200 second restriction, TMA is able to take advantage of its metering fix accuracy improvement to reduced the extraneous gap contribution to the buffer. Table 2-1 also shows that no fuel savings are expected when the TRACON Delay Setting is limited to 100 seconds (i.e. TRACON airspace delay cost is $12.88 per aircraft regardless of system). This reflects the fact that more TRACON delay is needed to absorb the system's metering fix variability than is available with the 100 second ceiling. Thus, no delay is shifted from the TRACON to the Center. However, with the less restrictive 200 second limit, TMA with it's improved metering fix accuracy is able to better distribute delay between the Center and TRACON. This reduces fuel costs for arrival aircraft during a rush as, on average, their nominal time spent in the TRACON is expected to be reduced. The alleviation of restrictions on TRACON delay absorption provides TMA greater freedom to exercise the optimization trade-offs depicted in Figure 1-1.

3. Multi-Center Traffic Manager Advisor

Multi-Center TMA enables traffic management coordinators in different Centers to mutually plan arrival traffic flow into a common airport. Multi-Center TMA resolves situations in which no one Center has complete information of the overall traffic handling requirement. Without inter-Center data exchange and coordination, each TMA operation in different Centers could independently generate traffic flows that jointly overload their common TRACON. Traffic congestion in the TRACON would require intervention to restrain the inbound traffic flow, propagating delay upstream. Delay propagation due to coordination complexities could be particularly severe in congested areas characterized by a heavily traveled network of nearby airports, such as the Northeast Corridor, where short flights limit reactive traffic flow adjustment options and planning is critical.

Multi-Center TMA System Operation

Multi-Center TMA develops a sequencing and scheduling plan for arrival aircraft to an airport that directly supports operations in each Center feeding traffic to the TRACON serving that airport, but is based on optimizing runway system and extended terminal airspace operations. TMA aids air traffic controllers and traffic management coordinators in each Center in the establishment of efficient inbound traffic flows and distributions and in the timely delivery of aircraft to metering fixes at each Center's boundary with the TRACON.

Of the 10 airports under study, the following four have been identified in a previous study [ref.15] as sites for Multi-Center TMA service:

- Newark (EWR)
- Kennedy (JFK)
- LaGuardia (LGA)
- Philadelphia (PHL)

The remaining six subjects are Single-Center TMA sites serving:

- Denver (DEN)
- Dallas-Ft. Worth (DFW)
- Minneapolis (MSP)
- Chicago O'Hare (ORD)
- Los Angeles (LAX)
- San Francisco (SFO)

Multi-Center TMA Potential Benefits

While the implementation of Multi-Center TMA is technologically and operationally more complex than TMA implementation at one site, the flight delay reductions achievable by Multi-Center TMA may be essentially identical to those of Single-Center TMA. The benefits due to TMA accrued by arrival flights into a TRACON described in the preceding section of this report are assumed to be equally applicable regardless of whether that TRACON is served by one or multiple Centers.

4. Passive Final Approach Spacing Tool

Passive FAST develops a sequencing, scheduling and runway assignment plan for arrival aircraft to an airport that directly supports TRACON operations and is based on optimizing runway system and terminal airspace operations. pFAST aids TRACON air traffic controllers in finalizing landing runway assignments and in achieving efficient runway system utilization.

The generic software modules that generate aircraft routes, trajectories and ETAs are common to pFAST and TMA. Currently, a joint TMA-pFAST deployment serving an extended terminal airspace may implement separate software systems, with redundant modules, for both the Center and TRACON, with appropriate two-way data link service. When deployed jointly with TMA, the pFAST ETAs and runway assignments at the metering fix for new aircraft entries into the TRACON airspace should be compatible with those of TMA. In either joint deployment with TMA or in stand-alone mode without TMA, pFAST continuously updates aircraft ETAs and STAs along trajectories between the metering fix and the runway and updates runway assignments. For any aircraft, pFAST computes ETAs, performs sequencing and scheduling with subsequent potential conflict resolution, and determines runway allocation based on an assessment of delay impacts.

pFAST displays textual advisories to controllers describing runway assignment and sequence for each aircraft. These advisors are shown in the flight data blocks on the controllers' traffic situation display. The TRACON controller may change the sequence and runway assignment using keyboard entry. ETA and STA timeline and other data are displayed to TRACON traffic managers, and could be transmitted for display at Centers and ATC towers.

pFAST System Operation

The pFAST sequencing, scheduling and runway assignment updates are based on radar and flight data received from the Center and TRACON computer systems and Center controller inputs. The radar and flight data are used to generate ETAs for each aircraft in the TRACON airspace. This airspace typically covers an area within 30 to 40 nmi radius of a major airport and below 10,000 to 12,000 feet above the surface. A set of ETAs are computed for an aircraft for route alternatives which allow for speed, horizontal and vertical maneuver variations. These routes are determined according to current airport runway system configuration and terminal area traffic plan, eligible runway, geographic section of airspace, engine type, approach segment (e.g., downwind, final, base, etc.) and aircraft state. ETAs along each route are derived from a 4-dimensional trajectory generated through the specified route waypoints using aircraft state, atmospheric grid, and vertical and speed constraint data.

pFAST sequences and schedules aircraft at defined time step intervals along each trajectory while maintaining proper spacing and avoiding conflicts. Groups of time steps define trajectory segments (e.g., final, left base leg, long-side downwind, etc.) which are used to correlate aircraft to compare and define relative sequence order. Aircraft sequence positions determined within each segment are combined, by merging trajectory segments, to determine the landing sequence for each runway. STAs are calculated based on the sequence plan and corresponding trajectories.

An aircraft's trajectory segments are searched for potential violation of separation requirements with other aircraft. In the case of a potential conflict, pFAST will invoke resolution algorithms to manipulate one or more trajectories based on the range of maneuver variations available and associated ETAs. STAs are adjusted accordingly.

pFAST balances aircraft landing assignments among the eligible runways to reduce overall runway system delay, subject to constraints adapted to local operating procedures. When triggered by traffic events (e.g., metering fix crossing, change in trajectory segment, controller intervention entry, missed approach) during an aircraft transit of the TRACON airspace, the process examines trial solutions to assess the runway utilization gains potentially obtainable by changing a previous runway assignment. pFAST defines the preferred runway for each aircraft in the landing sequence and selects a set of aircraft eligible for reassignment. The preferred runway is based on the mapping relationship between an aircraft’s feeder gate and runway, aircraft engine type and weight class, and considerations pertaining to controller or airline procedures and preferences. Aircraft eligibility for runway reassignment is determined largely by a runway allocation window defined for each runway. An aircraft with an ETA between the “start testing runway allocation time horizon” and the “freeze runway allocation time horizon” is eligible for reassignment. pFAST calculates estimated schedules and delays for the eligible aircraft for their current and alternative runways. pFAST then applies criteria encapsulating facility procedures, delay reduction and controller heuristics to narrow this set to a most likely aircraft to be reassigned. From this reduced set, pFAST selects an aircraft whose runway reassignment is most likely to have the greatest delay benefit to the overall arrival operation. pFAST tests the aircraft's proposed new runway in the full sequencing and conflict resolution cycle with all other aircraft. The resulting trial sequence, schedule, delay and conflict resolution data is evaluated to confirm or reject the proposed runway reassignment and associated resequencing and rescheduling.

pFAST Potential Benefits

pFAST provides a capability to reduce flight operating costs, noise exposure and noxious emissions. These benefits are derived from reduced delays due to more efficient runway and airspace system utilization. pFAST improves system utilization by determining efficient runway assignments, trajectories, sequences and schedules for terminal area arrival aircraft, and displaying the corresponding landing runway assignment and sequencing advisories to TRACON controllers. The pFAST advisories are designed to balance the use of all available runways and sequence aircraft to reduce delay.

The pFAST runway balancing process increases system efficiency by assigning aircraft to the runway that minimizes overall delay.

The advisories enhance controllers’ ability to mentally structure and visualize the arrival traffic plan and efficiently manage merging operations in the TRACON airspace relative to current operations. Controllers use the runway assignment and sequence advisories to generate TRACON arrival clearances in conformance with the pFAST traffic optimization plan, resulting in a reduction in the variance between the actual and planned aircraft trajectories. Here, the reduction is based on the comparison of the variance relative to the manually projected trajectory in the current system versus the variance relative to the pFAST-optimized planned trajectory. The improvement in aircraft position accuracy with respect to the planned position (i.e., reduction in aircraft position uncertainty) implies a reduction in the variance between actual and planned aircraft spacings. This pFAST-derived improvement in the controllability of spacing between successive aircraft effectively achieves a reduction in the excess spacing buffer.

pFAST enables controllers to better utilize the runway and airspace system relative to current operations through reduced aircraft position uncertainty and improved runway balancing and aircraft sequencing. These pFAST benefits mechanisms are further examined in the following paragraphs.

pFAST Aircraft Position Uncertainty

A previous study [ref.15] analyzed pFAST operational impacts using the results of a pFAST prototype field test at DFW in combination with analytical formulations and computerized simulations. Field test radar data recordings of traffic during current system and pFAST operations were used to determine aircraft actual crossings of the arrival runway threshold and the corresponding aircraft separations. These field test data were combined with modelings of TRACON operations to evaluate the excess spacing buffer contribution of aircraft position uncertainty.

The modelings simulated aircraft movement from metering fix to threshold for the DFW TRACON for the four nominal arrival routings shown in Figure 4-1 and 4-2. The position variance of the aircraft at various points along their assigned nominal trajectories were analyzed based on perturbations of various parameters affecting flight performance. In the end, the analysis focused on the runway approach segments between the point of final controller advisory and the runway arrival threshold. The final controller advisories, shown as triangles in Figures 4-1 and 4-2, are either a turn-to-base vector from downwind approaches or a deceleration advisory for straight-in approaches. This action effectively would negate the upstream trajectory errors accumulated between the metering fix and the point of final controller advisory.

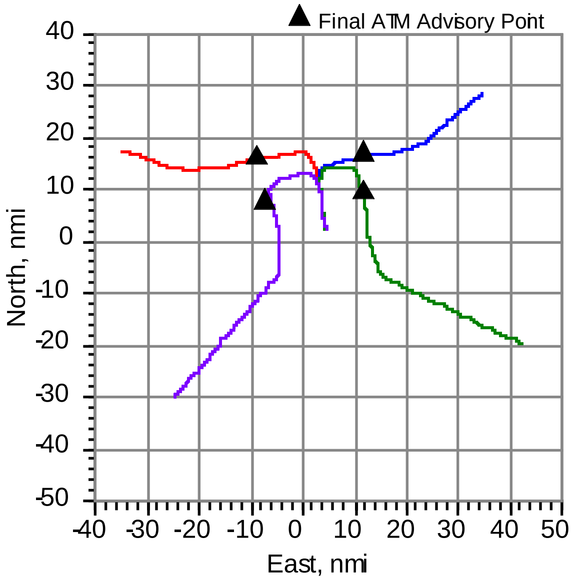


Figure 4-1 Modeled Nominal Approach Trajectories, Plan View

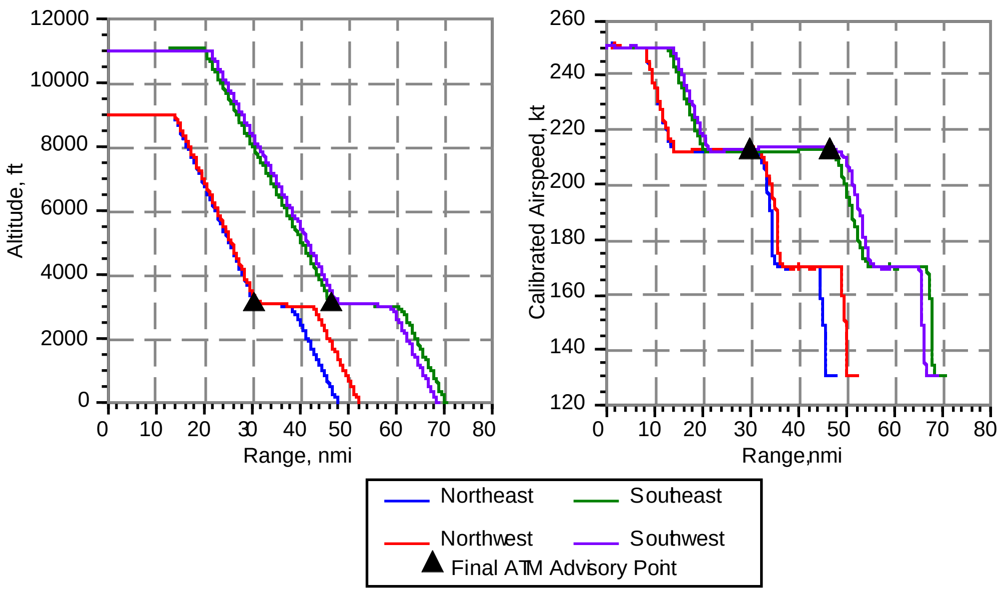


Figure 4-2 Modeled Nominal Approach Trajectories, Vertical Profile and Speed Schedule

Aircraft position accuracy values were determined for all possible aircraft pairings by varying threshold crossing speeds for the different aircraft weight classes. The aircraft position error distributions were used in analytical models to identify their contribution to the excess spacing buffer at the runway threshold. These values were calibrated (i.e., scaled proportionately through iteration) to fit the observed aircraft spacings obtained from the field tests to produce matrixes of threshold excess spacing buffer contributions due to aircraft position uncertainty. The matrix shown in Table 4-1 compares buffers between current system and pFAST operations.

Table 4-1 Arrival Aircraft Position Uncertainty Contribution to the Runway Threshold Excess Spacing Buffer

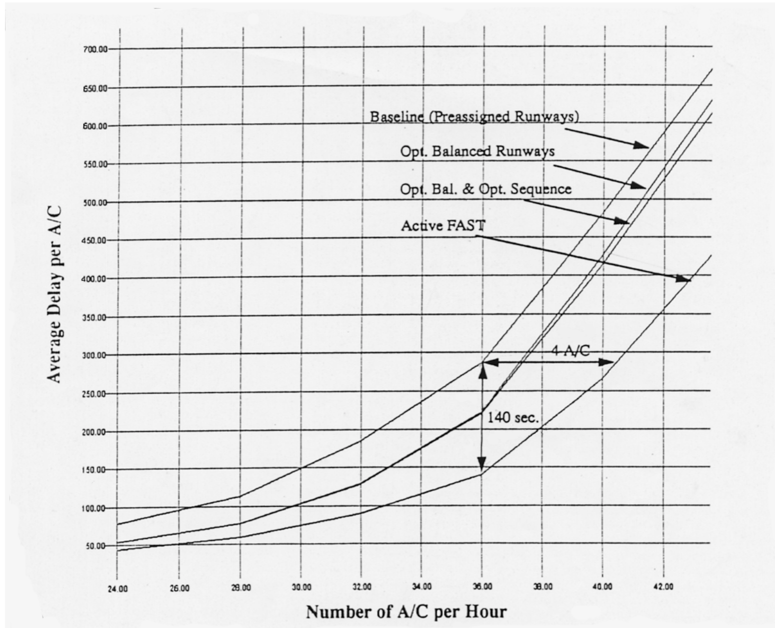
Leading Aircraft	Small	Large	Heavy	
	Current System			
Small	25.7 sec	25.1 sec	25.1 sec	24.6 sec
Large	27.8 sec	25.2 sec	25.2 sec	24.5 sec
757	28.9 sec	26.4 sec	26.4 sec	25.7 sec
Heavy	30.5 sec	28.2 sec	28.2 sec	25.7 sec
	pFAST			
Small	23.6 sec	23.3 sec	23.3 sec	23.0 sec
Large	25.0 sec	23.2 sec	23.2 sec	22.8 sec
757	25.6 sec	24.0 sec	24.0 sec	23.3 sec
Heavy	26.6 sec	25.1 sec	25.1 sec	23.3 sec

pFAST Runway Balancing and Aircraft Sequencing

Previous studies [ref.19,20,21] of pFAST have examined runway balancing and aircraft sequencing by evaluating their impacts in terms of equivalent excess spacing buffer reductions at the arrival threshold. The premise being that an inefficient runway operation reduces throughput which can mathematically be represented by increased average spacing between aircraft. This buffer is reduced with the implementation of pFAST.

The excess spacing buffer increase due to non-optimal runway balancing under current operations without pFAST was estimated [ref.15] from prior simulation work performed at NASA Ames Research Center. Figure 4-3 shows the simulation results which compare average delay per rush arrival under current manual (baseline) operation and both the passive and active versions of FAST. [ref.19] The delay data for current and pFAST runway balancing operations were used, with allowance for queuing effects, to mathematically derive the mean difference in aircraft time spacing between the two operations. This resulted in a runway balancing buffer contribution of approximately 2.3 seconds per aircraft pair when pFAST is not in place. This estimate fits the pFAST prototype field test results at DFW. [ref.21] The runway balancing buffer reduction is assumed achievable at airports operating with 3 or more arrival runways. With less than 3 runways, the runway balancing improvement of pFAST is assumed to be negligible.

The plots in Figure 4-3 indicate that improved sequencing provides a small benefit compared to the other mechanisms, such as runway balancing and improved in-trail position accuracy. This result concurs with other research. [ref.20]



<u>Assumptions</u>
MF Delivery Error = 0, TRACON Delay Setting = 60 seconds
2 Runways, Statistically Balanced Traffic
Source: Reference 19

Figure 4-3 FAST Average Rush Delay Savings

5. Active Final Approach Spacing Tool

Active FAST performs the same traffic analysis, prediction and resolution functions as pFAST, but assembles and presents information to TRACON air traffic controllers that are in addition to that of pFAST. Using the same capabilities as pFAST, aFAST develops sequencing, scheduling and runway assignment plans for arrival aircraft to an airport. As does pFAST, this process directly supports TRACON operations and is based on optimizing runway system and terminal airspace operations. As does pFAST, aFAST aids TRACON air traffic controllers in efficiently utilizing the terminal airspace and runway system by identifying optimum landing runway assignments and sequences. in achieving. However, beyond pFAST, aFAST displays advisories to controllers which are specifically directed to accurately positioning and spacing aircraft on TRACON arrival patterns, especially the final approach.

aFAST System Operation

The aFAST operating functionality is the same as that described in the preceding section for pFAST except for expanded information display. aFAST displays textual and graphical advisories to controllers describing runway assignment and sequence, indicated airspeed and heading for each aircraft. The textual advisors are shown in the flight data blocks on a controller's traffic situation display. Recall pFAST displays only the runway assignment and aircraft sequence in the data block. In addition to this textual data, aFAST graphically presents the speed and heading advisories on the controllers' traffic situation display. A special airspeed advisory symbol is displayed as a marker at the advised location to issue the airspeed instruction. A special heading advisory symbol is displayed as a marker at the advised location to issue the turn instruction. The advised magnetic heading in degrees is displayed textually next to this marker symbol, and a pictorial arc is displayed to depict the predicted turn path, accounting for speed, heading and winds aloft. Color coding would be applied to enhance the symbolic information.

As does pFAST, aFAST enables the TRACON controller to change the sequence and runway assignment using keyboard entry. ETA and STA timeline and other data are displayed to TRACON traffic managers, and could be transmitted for display at Centers and ATC towers.

aFAST Potential Benefits

aFAST provides an enhanced capability, relative to pFAST, to reduce flight operating costs, noise exposure and noxious emissions. These benefits are derived from reduced delays due to more efficient runway and airspace system utilization. aFAST improves system utilization analogously to pFAST, but displays an expanded set of data to controllers. aFAST determines efficient runway assignments, trajectories, sequences and schedules for terminal area arrival aircraft, and displays the corresponding landing runway assignment, arrival sequencing, airspeed and heading advisories to TRACON controllers. The aFAST advisories are designed to balance the use of all available runways to reduce delay and sequence and space aircraft to allow efficient merging of separate traffic streams according to the best achievable aircraft ordering by type.

Controllers use the aircraft airspeed and heading advisories in conjunction with the runway assignment and sequence advisories to maneuver aircraft so that actual aircraft positions, sequences and landing times conform closely with the aFAST traffic optimization plan. The advisories facilitate arrival merging and spacing operations throughout the TRACON. The airspeed and heading data displayed for the final controller advisories are particularly effective in controlling spacing along the final approach. These advisories identify precisely the content and timing of the turn-to-base vector from a downwind segment or deceleration for straight-in approach that would achieve the trajectory planned by pFAST to optimize runway utilization. aFAST effectiveness is enhanced by its ability automatically to resequence and reschedule trajectories in response to changing circumstances such as a late turn-to-base or a missed approach. A reduction in the variance between the actual and predicted trajectories results, achieving an improved arrival time delivery accuracy at the runway threshold relative to current operations.

Benefits derived from aFAST runway balancing and sequences would be analogous to those of pFAST. However, aFAST further reduces the variance between actual and planned aircraft position. This improvement in aircraft position uncertainty results in a further reduction in the excess spacing buffer applied to compensate for inaccuracies in the predicted position of aircraft within the TRACON airspace. A previous study [ref.22] which evaluated excess spacing buffer reductions attributable to aFAST relative to current operations was updated [ref.23] to account for the results of the DFW prototype field test. The update indicates that these additional reductions due to aFAST are approximately equal to those of pFAST.

6. Collaborative Arrival Planning

CAP provides a means for airlines to communicate their arrival flight preferences, status, and AOC information to the air traffic management service provider for incorporation into ATM strategies and clearances, and a means for ATM to communicate real-time ATM status and prediction information to airlines. CAP consists of the airline and ATM automation communication infrastructure for one-way and two-way data transmission of air traffic status and near-term prediction information to the airlines, and airline arrival flight preferences, as well as, other airline-sensed data (e.g., updated arrival aircraft performance characteristics, winds) to the ATM service provider. The CAP automation assists in generating and communicating user preference and ATM data using adapted DST software and new communication network capabilities.

The enhanced airline-ATM information exchange provided by CAP enables increased accommodation of airline arrival aircraft trajectory preferences, facilitates new air traffic operational concepts such as intra-airline arrival slot swapping, and improves ATM clearance decisions through more accurate air traffic trajectory predictions.

CAP System Operation

CAP is currently in the early stage of automation technology development, and plans for future CAP features and CAP-supported air traffic operations are maturing. An evolutionary technology development process is expected as described in the following paragraphs.

The near-term communication of ATM status and prediction information is being facilitated through the establishment of a CTAS-to-airline data exchange through the use of a TMA "repeater" at the American Airlines' (AAL's) AOC near DFW airport. This repeater system consists of a one-way ground-to-ground computer network that transmits data from the Fort Worth ARTCC to the American Airlines AOC to display TMA-generated Planview and Timeline Graphical User Interface information. The repeater provides the AOC with near-real time updates of air traffic information such as estimated arrival times, expected flight delays, arrival sequences, airport arrival rates, and airport configuration. This CTAS repeater provides airline access to TMA data except for non-AAL aircraft identifiers.

Other expected near-term passive CAP data exchange developments include the creation of an airline-to-CTAS data exchange. The airline-to-CTAS data exchange will be developed to transfer timely AOC data to CTAS to improve its trajectory predictions and advisories. Some of the expected data to be exchanged include departure data from satellite airports, aircraft weight, and aircraft-sensed winds data. A number of additional potential AOC and ATM data elements to be exchanged are under consideration including aircraft-specific runway landing constraints (e.g., some aircraft may not be permitted to land on certain airport runways due to weight limits or mechanical failures), and landing system capabilities (e.g., Category I, II or III).

Future development of CAP functionalities will be focused on a two-way airline-ATM data exchange of arrival flight information. CAP tools will be developed for the airline dispatchers, operational coordinators, and ramp tower managers to efficiently generate airline aircraft arrival preferences. This preference information is expected to include aircraft arrival sequence and schedule, runway preferences, gate preferences, and preferred Mach number/calibrated airspeed (CAS) descent schedules. Additional CAP tools will be developed for the ATM traffic management coordinators and, possibly the air traffic controllers if operationally feasible, to enable the processing and evaluation of and response to (if necessary) airline arrival preferences within ATM operating constraints.

One expected future operating concept that could be supported with CAP is intra-airline arrival slot swapping. The concept will allow an airline to swap arrival slots among its inbound arrival flights in the DST-adapted airspace to enable the most time-critical flights to land first. Airlines would be interested in this capability in situations such as the possible slot swap between:

1) a flight with low fuel reserves with a flight with significant fuel reserves,
2) a flight whose gate is not yet available with a flight whose gate is available, and
3) flights in different banks during irregular operations conditions when air traffic from consecutive arrival banks overlap.

CAP Potential Benefits

CAP provides a capability to enhance capacity, flexibility, predictability and improve airline resource allocation decisions. The potential benefits of CAP accrue to the airlines using CAP tools, the ATM service provider, non-CAP-using airspace users, and airline customers (e.g., passengers and cargo owners). Potential benefits are shortly identified for both passive CAP data exchanges (including both CTAS-to-airline and airline-to-CTAS exchanges) and for future CAP ATM/Airline decision support tools. Airline dispatcher and ramp personnel contributions [ref.24,25,26] are the source of a number of the potential benefits.

CAP Passive Data Exchange Analysis

CTAS-to-Airline Data Exchange -- Near-term benefits will accrue to the airlines with a CAP repeater installed at their AOC displaying air traffic operations data for major hub airports. These benefits result from AOC use of DST-provided reports or projections of flight arrival times and terminal delays.

The display of predictions of arrival times is a significant accuracy improvement over current airline predictions. Preliminary NASA research results [ref.27] indicate that at "change-over", typically 20-30 minutes away from landing, CTAS landing time prediction accuracies reduce expected standard deviation time errors from the airline's level of 5 minutes down to 3 minutes. This better knowledge of aircraft arrival times results in better airline resource allocation decisions for such resources as gates, ramps, aircraft, flight crews and ground operations equipment and personnel, improved arrival and departure coordination (i.e., "hold-go" decisions) and reduced baggage mishandling costs. Improved AOC knowledge of terminal airspace delays will also provide benefits due to reduced low-fuel diversions. In addition to these previously-mentioned benefits, additional benefits have been observed through CAP repeater field tests. [ref.27]

In the case of airport ground operations equipment and personnel, because of the uncertainty of flight arrival times in arrival banks, airlines tend to provide one set of ground equipment and personnel per gate. These equipment and personnel are dedicated to serving their particular gate around-the-clock regardless of when the next arrival flight at that gate is scheduled. With a better prediction of flight arrival times provided by the CAP repeater, the ground operations equipment and personnel could be assigned to more than one gate. This would then allow airline airport personnel to improve equipment and personnel utilization, thereby, achieving ground resource operational cost savings. In addition, overtime costs that are incurred by the airline due to the unpredictable nature of the gate operations could be potentially reduced through the improved utilization of ground personnel and equipment.

In the case of the better arrival and departure coordination, airline station managers often must make decisions on whether to hold departing aircraft for late arriving passengers, and baggage. The quality of these decisions have a direct impact on the direct operating costs of the airline, as well as the service to the revenue-paying passengers and cargo. The improved accuracy in flight arrival time predictions provided by the CAP repeater leads to improved arrival and departure management and provides a reduction in the airline direct operating costs, an improvement in airline service, and, an improved predictability to customers in destination arrival time.

The more accurate DST-predicted arrival times offer the potential for the airline airport personnel to reduce baggage mishandling costs. Typically, one hour before an aircraft's arrival, ramp personnel decide arriving aircraft gate allocations and coordinate this information with baggage personnel.

Baggage personnel use this information to determine to which gates bags need to be routed. If gate allocations are switched at later times, tight schedule connections may result in baggage misconnections and significant baggage mishandling costs. The more accurate arrival time predictions provided by CAP could improve the gate allocation decisions, reducing the chance of baggage misconnections and resulting baggage mishandling costs.

The CAP repeater provides more accurate estimates of terminal air traffic delays than otherwise available to AOC dispatchers. This more accurate estimate could lead to a reduction in the number of airline flight diversions. This reduction in the flight diversions would result during periods of significant aircraft holding and when the flight did not load a large amount of extra fuel (which can be due to a number of reasons that include good weather forecasts and a lack of aircraft weight usable for fuel because of extra payload). Because of IFR procedures that allow for potential air-ground communications failure, a controller will issue a holding clearance and an "expect further clearance" instruction for a given, often long period of time (e.g., 15 minutes or more). If a flight is low on fuel and the "expect further clearance" message is the best available estimation on how much longer the flight will have to hold, the pilot, in consultation with a dispatcher, may choose to divert to an alternate landing airport. However, with the CAP-enhanced repeater in the AOC, the dispatcher can examine the DST-predicted delay times and estimate the flight's holding time. If this delay prediction time is significantly less than the "expect further clearance" time and within the diversion tolerance of the particular flight, a diversion can be avoided. This diversion avoidance can significantly reduce airline crew costs, fuel costs, downstream schedule delays and cancellations, and possibly customer lodging costs, if late at night, and increase customer loyalty from reduced missed connections and lengthy travel delays. Previous NASA CAP field demonstrations [ref.27] observed such reductions in potential diversions and identified an additional diversion-related benefit mechanism. In the case when an aircraft is sure to divert, the additional CAP arrival prediction accuracy will allow the aircraft to divert earlier, saving additional fuel costs.

Finally, additional benefits have already been observed at NASA CAP field demonstrations which included reduced workload and improved airline bank management. The CAP field demonstrations suggest that the use of a CTAS "repeater" system helps to reduce the workload of FAA traffic flow manager, airline ATC operations coordinator, and airline dispatchers. The presentation of expected per aircraft delay times and other CTAS information reduced the number of phone calls from the airline ATC operations coordinator to FAA traffic flow management personnel asking for current airport and airspace status information. Additionally, the CAP field tests demonstrated the ability of the CAP Planview-Graphical User Interface (P-GUI) to support improved airline bank management by providing detailed aircraft location and holding status which improved airline dispatcher predictions of aircraft arrival times. These improved arrival time predictions provided airline operations coordinators with better knowledge to plan aircraft equipment move-ups that resulted in better schedule integrity.

<u>Airline-to-CTAS Data Exchange</u> -- With the introduction of CAP technology that will enable future airline-to-CTAS data exchanges, specific data such as aircraft weight, airborne winds, departure data from satellite airports, aircraft-sensed weather, aircraft runway landing constraints, and landing system capabilities will provide additional CAP benefits. Expected benefits from each of these data exchanges are described below.

With the CAP exchange of AOC-derived aircraft weight data, there are a number of potential benefit mechanisms. CTAS incorporation of this aircraft-specific weight into its trajectory prediction algorithms will improve its 4D trajectory predictions, conflict predictions, and advisories. Previous NASA Descent Advisor field test data [ref.28] have suggested the potential for actual descent weight data exchanges to reduce CTAS TOD prediction errors by 1.3 nmi. Controller use of these improved advisories will result in improved airport throughput and reduced delays, more fuel efficient clearances, and reduced ATM interruptions. A pertinent fact is that significant changes in the CTAS advisories are likely to be incumbent upon the controller's use of future CTAS decision support tools such as EDA and A-FAST that provide the controller with specific speed, heading, and TOD advisories. An additional far-term benefit might exist whereby CAP exchange of aircraft weight information could be coupled with a change in the FAA in-trail separation rules from one based on aircraft type (which is related to maximum gross weight) to one based on the actual weight of the aircraft. If feasible, the potential benefits would likely be very significant, but would require an FAA loosening of separation rules that would go counter to the historical trend of being more conservative.[ref.29]

With the incorporation of AOC-provided airborne winds data into CTAS weather forecasts, additional benefits would result. Recent Massachusetts Institute of Technology/Lincoln Lab research[ref.30] suggests that the incorporation of FMS-derived winds data into NOAA RUC will significantly improve on-average wind field accuracy, and, potentially CTAS trajectory predictions. Similar to the previously-mentioned exchange of weight data, improved CTAS trajectory predictions should result in improved airport throughput and reduced delays, more fuel efficient clearances, and reduced ATM interruptions.

A CAP exchange of departure data from satellite airports should also provide potential benefits. Currently, CTAS builds in additional open slots into its arrival schedule based on historical knowledge of “pop-up” arrival flights departing from satellite airports (those located within the 250 nmi TMA planning horizon). If not filled within certain time constraints, these slots are dropped by CTAS. Even though this lack of empty slot persistence is not expected to impact runway throughput significantly, it will reduce arrival aircraft trajectory fuel efficiency. Assuming steady, slot-constrained air traffic demand, the creation of the empty slot and its subsequent dropping will require unnecessary accelerations and decelerations from aircraft when making or removing the interarrival gaps. CTAS incorporation of real-time departure scheduling updates would allow the reduction of the number of these excess slots and the subsequent reduction in excess fuel burned.

Finally, if adopted by the CAP program, additional benefits may be obtained through the airline communication of aircraft landing restriction and capability information. Aircraft-specific runway landing constraints from the AOC provides enhanced situational awareness for traffic management coordinators and controllers, improves the feasibility of DST-developed runway allocations, and facilitates the runway assignment process, resulting in reduced pilot-controller air-ground radio frequency congestion and more efficient runway allocations.

CAP ATM/Airline Decision Support Tools

A two-way exchange of AOC and ATM information and use of CAP decision support tools for the ATM and airlines will enable ATM incorporation of AOC data such as inter-aircraft arrival preferences, and aircraft trajectory preferences into aircraft movement clearances.

The transfer of AOC inter-aircraft arrival schedule and sequence preferences to CTAS automation in conjunction with implementation of operational concepts such as intra-airline arrival slot swapping offer the potential for a number of benefits. Airlines may experience reduced time-critical aircraft delays and reduced costs of misconnections, diversions, and cancellations, as well as, decreased revenue loss from dissatisfied customers. Also, under certain circumstances, the time-uncritical aircraft might experience improved fuel efficiency from slowing-down as opposed to “hurrying up and waiting”. The reduction of misconnections, diversions, and cancellations, benefits airline passengers and cargo owners through reduced delays, overnight stays, reduced lost future revenue, and associated complications. Additionally, intra-airline arrival slot swapping would provide a significant increase in airline arrival scheduling flexibility and enable smoothing of flight arrival traffic into the airport. The smoothing has the potential for reducing ground delays, especially on the ramp, due to a reduction in ground congestion and clearance complexity.

The provision by AOC of the trajectory preferences for individual arrival aircraft would support increased ATM sensitivity to and accommodation of user preferences. Assuming that incorporation of the individual aircraft trajectory preferences is operationally feasible within the ATM constraints, airlines benefit through lower direct operating costs and more flexibility based on their increased input into ATC clearances. Additionally, the AOC transfer of the individual arrival aircraft trajectory preferences (e.g., Mach/CAS speed schedules) to ATM automation leads to improved DST trajectory prediction accuracy and, upon controller use of DST-generated advisories, lead to improved traffic flow management strategies and arrival aircraft scheduling and sequencing. The increased throughput for all aircraft under air traffic control results in reduced air traffic delays and direct operating costs.

7. Expedite Departure Path

EDP develops an integrated traffic plan for departure aircraft that enhances utilization of the runway system and extended terminal airspace and accommodation of user preferences. EDP uses the high-fidelity, aircraft performance-based software modules to analyze routings, construct accurate flight profiles, resolve potential conflicts, and optimize trajectories. EDP determines sequencing and scheduling plans for use by traffic management coordinators, controllers in Centers, TRACONs and tower, and airline dispatchers in AOCs. EDP generates advisories to support the routing, sequencing, spacing, and vertical profile assignment of ascending aircraft, the merging of departure traffic into the en route traffic operation, and the balancing of departure traffic loading.

EDP System Operation

EDP is in the early phase of concept exploration and definition, and its design is evolving. Initial implementation may support TRACON operations, with subsequent expansion directed to Center and other facilities.

EDP synthesizes departure trajectory planning with TMA, pFAST/aFAST and CAP operations. This integration of automation functions enhances system performance by enabling more accurate situation analysis and producing better optimized sequencing, scheduling and trajectory planning solutions for arrival and departure traffic.

Operating functions identified [ref.1] for EDP include:

- Provide aircraft sequencing and departure gate balancing information to TRACON traffic management coordinators.
- Utilize conflict probe functionality to expedite departures that cross arrival routes by determining when unrestricted climbs can be given to specified aircraft (in en route airspace).
- Meter and/or provide clearance advisories for departing aircraft that merge over a given fix.
- Provide optimal release times for tower controllers at primary and satellite airports.
- Provide gate push-back recommendations to airline operational control facilities.
- Provide conflict-free, fuel-efficient speed and turn advisories to improve utilization of terminal airspace.

In addition to integration with the AATT terminal DSTs, EDP would interface with surface and en route DSTs.

EDP Potential Benefits

EDP provides a capability to reduce flight operating costs, noise exposure and noxious emissions. These benefits are derived from reduced delays due to more efficient runway and airspace system utilization, including more efficient trajectories. Potential benefits are addressed in the following paragraphs using DFW as an example.

Improved Trajectory Control -- EDP would apply the sequencing and scheduling capabilities of TMA, pFAST and aFAST to departure traffic, improving trajectory prediction and control accuracy for arrivals and departures. The reductions in the variance between actual and planned aircraft position would result in reduced excess spacing buffers for departure traffic as well as arrival traffic that interact with departures. The advisory service generate by EDP would be comparable to that of aFAST, and the spacing buffer reduction of EDP could be similar to that of aFAST.

Improved Runway System Utilization -- EDP would expand the functionality of TMA-FAST by including departures in the development of strategies to optimize traffic movement. With respect to runway system utilization, the automation would simultaneously account for both arrival and departure traffic sequencing and spacing requirements. DST integration of the landing and takeoff schedule could improve total runway system throughput at those airports where arrival and departure procedures interact. DFW runway arrival operations are largely independent of departures on parallel runways, and the potential effectiveness of EDP in reducing runway system-dependent delay may not be demonstrated at DFW. Such benefits could be significant at other airports with crossing or closely spaced runways. However, even at DFW, situations may arise in which DSTs with integrated arrivals and departures could improve operations. For example, during very severe weather, current ATM practices tend to place emphasis on landing the arrivals, while holding departures on the ground. The airport surface and terminal gates could become extremely congested with both the arrival and departure aircraft. Integrated arrival and departure automation could set an appropriate traffic sequence that would release a sufficient number of departures as early as practicable to relieve the ground congestion. In this situation, the automation would be augmenting the controller's decision making processes during a period of severe workload (i.e.: providing information or guidance to controllers that otherwise might not be considered because of workload constraints).

Improved Departure Trajectories -- Standardized departure routes and profiles are used to procedurally separate traffic. These procedures restrict trajectory flexibility, and often increase flight distances and impose non-optimal climb profiles. Altitude restrictions may require departures to extend their flight below 10,000 ft, which precludes the pilot from invoking a user preferred speed schedule which would continuously increase speed above 250 knots. At DFW, some departure procedures tunnel departures under arrivals. Controllers do expedite climbs when arrivals clearly are not a factor to the departure trajectories. Improved trajectory control with EDP may enable controllers more frequently to approve expedited climbs. In airspace assigned primarily to departures, the management of overtaking, crossing and merging situations may by improved by EDP-generated sequencing and spacing advisories. An EDP function analogous to aFAST would provide turn and speed command advisories that could enable better ATM sensitivity to user preferred climb trajectories.

Improved Departure Gate Sequencing -- Adherence to en route spacing rules is required for aircraft crossing the departure gate at the TRACON outer boundary. The transition from 3 nmi to 5 nmi minimum spacings is accomplished by the terminal controllers using vectoring, speed control and altitude restrictions. The severity of the rate of occurrence of potential conflicts at a single departure gate is dependent on the takeoff sequence established by the tower cab local controller. Ideally, a series of departures should be destined to different departure gates so that spacing at any one gate is provided. The ordering of departures at the runway is not totally controllable, and the ideal sequence often may not be achievable. Takeoffs may be delayed to satisfy en route spacing procedures or the delay may be absorbed in the terminal airspace by adjusting the trajectory. These solutions would adversely affect user flight costs. EDP-based scheduling of departures would take the departure routing into account to improve operations. We note that each of the four main departure corridors of the DFW TRACON airspace has four outbound radials at the boundary between the TRACON and Fort Worth Center. The four radials in each corridor diverge from each other and are spaced about six miles apart to satisfy minimum separation rules. Observations indicate that the DFW tower controllers routinely are able to sequence the departures among the radials so that overtaking situations at any one radial may not be a major issue.

Reduced Taxi Delay -- The establishment of a takeoff schedule by EDP would enable operators to assign terminal gate departures times to minimize delays during taxiing. The EDP-generated schedule could be used by ATM surface movement automation to plan taxi routings and sequences.

Improved Coordination of Satellite Airport Departures -- EDP could greatly alleviate coordination work between a hub airport tower and local airport towers needed to fit departures from satellite airports into the traffic pattern. Special effort may be needed at some sites to build "holes" in the departure stream from the hub airport for an IFR departure from satellite airport. With respect to DFW, local airports include Dallas Love Field, Addison, Meacham, Alliance, and military bases.

Although the interactions among airport runway system use, trajectories, departure gate sequencing, and local airport coordination are complex, EDP is a method to leverage ATM automaton to produce operational improvements.

8. DST Potential Benefits Analysis Factors

This terminal DST potential benefits analysis is part of a larger coordinated effort to evaluate multi-domain impacts. This analysis is designed to be cross-comparable with parallel assessments of en route, terminal surface, and airborne DSTs. The comparisons will be based on analyses of operational improvements due to DSTs, evaluations of associated technical performance metrics, and translations of the performance impacts to annual and nationwide economic benefits. The metrics are indicators of ATM system performance with respect to: capacity, flexibility, predictability, safety, access, and environment. Representative performance metrics for each category are listed in Table 8-1.

Table 8-1 Representative Technical Performance Metrics

Performance Metric Category	Example Performance Metric
• Capacity	Increased runway system and airspace throughput; reduced flight time and flight operating cost
• Predictability	Increased trajectory prediction accuracy; better schedule adherence with reduced delays within planned schedules
• Flexibility	More user-preferred trajectories (including more fuel-efficient descents and climbs, reduced airspace restrictions, more direct routing, and fewer and less severe trajectory interruptions)
• Safety	Reduced numbers of collisions, near misses, and ATC operational and flight technical errors, and less severe consequences of such incidents
• Access	Increased availability of ATC services
• Environment	Reduced noise exposure and noxious emissions

An objective of this study is the quantitative examination of capacity, flexibility, and predictability and the associated economic impacts. Access and environmental impacts would be addressed qualitatively. The benefits impacts analyses are performed for a base year, 1996, and a future year, 2015.

The potential benefits analysis process is described in the remainder of this section by reviewing the DST operational impacts, relating these impacts to specific benefits metrics, conceptualizing the overall analysis process, and identifying the applicable modeling and analytical procedures for evaluating the metrics.

DST Operational Impacts

The AATT tools will enable improved aircraft trajectory control accuracy, improved knowledge of user preferences by ATM, and improved flight planning and scheduling flexibility by users. These improvements will increase ATM operational effectiveness relative to the current baseline operation and incrementally as tool implementations evolve. Operational improvements directly associated with AATT DSTs include:

- Reduced excess spacing between successive aircraft;
- More cost-effective distribution of delay between Center and TRACON airspace;
- Increased integration of ATM and user flight management operations, and increased accommodation of user preferences;

• Increased integration of arrival, departure and en route operations.

The potential benefits of these operational improvements include reduced aircraft direct operating costs, improved flight scheduling and planning, and enhanced safety, access, environmental factors, and controller and pilot productivity. The following paragraphs briefly review the operational improvements, which were described in the preceding sections for each DST, and their potential benefits impacts.

Excess Spacing

Trajectory prediction uncertainty generates an excess spacing buffer between successive aircraft. Figure 8-1 illustrates the factoring of predicted position uncertainty into the planning of the downstream spacing between successive aircraft.

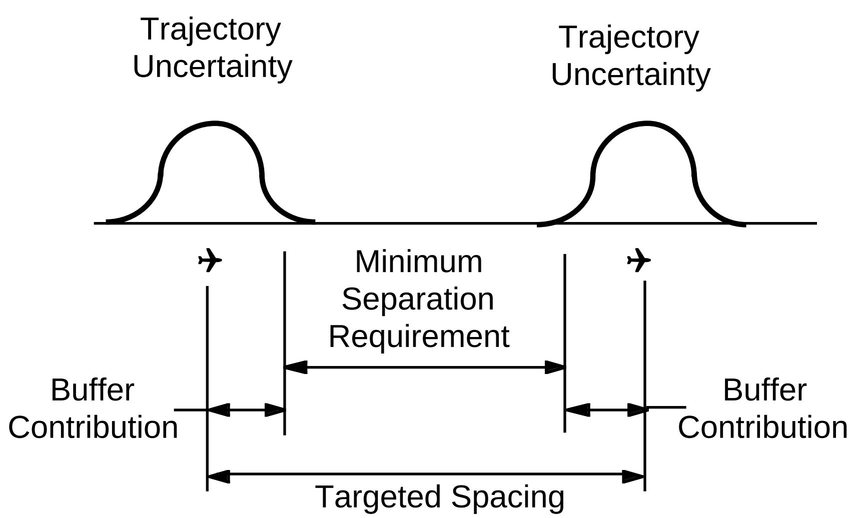


Figure 8-1 Planned Spacing Composition

The buffer contribution of each aircraft represents the excess spacing applied to prevent a subsequent violation of separation minima due to trajectory variance. The buffer size would vary directly with the magnitude of trajectory variance, i. e., the larger the variance, the larger the buffer required to minimize the probability of a potential violation.

Given a planned spacing between successive aircraft, the actual spacing would be determined by trajectory variations encountered during flight. Figure 8-2 illustrates the difference between the planned spacing and its realization. In this example, the actual spacing resulting from trajectory perturbations is greater than that planned, resulting in excess spacing. A different example could show a loss of actual separation relative to the plan, but the resulting spacing would not be less than the minimum separation requirement because of controller intervention.

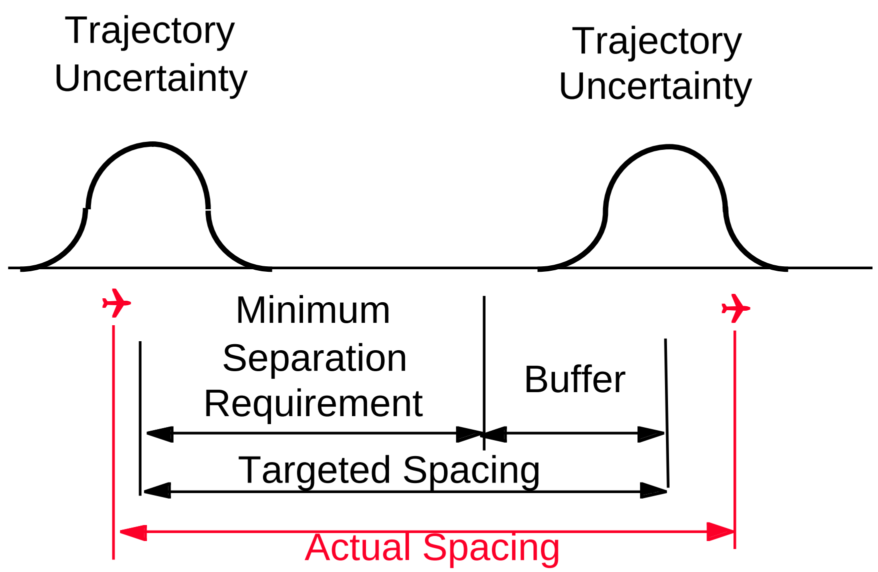


Figure 8-2 Actual Spacing Example

Excess spacings due to trajectory uncertainty embedded in process of planning and implementing fix crossing schedules may generate downstream extraneous gaps. For arrival aircraft in a terminal area, an extraneous gap at the runway threshold could result from aircraft delivery inaccuracy at the metering fix crossing. Figure 8-3 depicts an excess interarrival spacing at the runway threshold which includes an extraneous gap propagated from the metering fix. In this example, the extraneous gap could not be resolved in the terminal airspace.

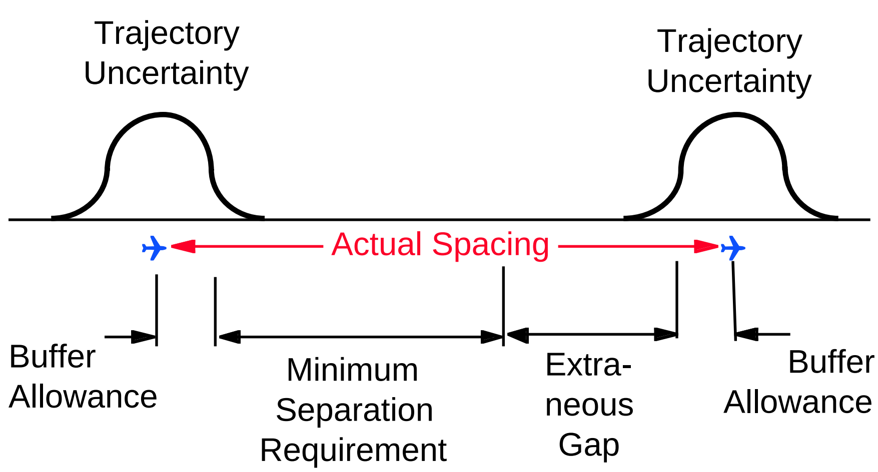


Figure 8-3 Excess Spacing with Extraneous Gap

The reduction in trajectory uncertainty due to the DSTs would result in a reduction in the size of the excess spacing buffer needed to compensate for trajectory variances. The smaller buffer would reduce the spacing applied between successive aircraft, as set by the DST scheduling process. Improved trajectory accuracy also would reduce the propagation of extraneous gaps in the spacings actually realized. The resulting overall reduction in excess spacing would increase the throughput of the airspace and runway system. The increased throughput would reduce delays experienced by arrival aircraft when demand approaches or exceeds the capacity of the runway system, and would enable more efficient utilization of arrival routings and fixes. These reduced delays would result in reduced fuel and time costs incurred by aircraft operators. Departure traffic would also realize operating cost benefits through more efficient use of runway systems, departure routings and departure fixes.

Delay Distribution

The DST delay distribution function allocates aircraft delay between Center and TRACON airspace during busy traffic periods to achieve an optimum balance between fuel burn savings and runway system throughput. The delay distribution function performs a trade-off between the advantage of absorbing delay at the higher en route altitudes, where fuel efficiency is greater, versus the advantage of packing more aircraft in the terminal airspace to ensure that aircraft are continually available to use the runway system. Excess allocation of delay to the Center airspace would degrade runway system utilization. As trajectory prediction and control accuracy is improved, less delay time is needed to be absorbed in the TRACON airspace to maintain high runway system throughput.

The improved trajectory accuracy afforded by the DSTs would increase the proportion of delay that should be taken in the Center airspace for a given runway system throughput, providing additional cost savings due to the more fuel-efficient trajectories. These savings differ from those due to reduced excess spacings in that the excess spacings determine the runway system throughput and the associated amount of delay whereas delay distribution determines how the given amount of delay is taken.

ATM and User Preference Integration

The DSTs are designed to be sensitive and responsive to user preferences by accounting for user optimization objectives and allowing for real-time data exchange and collaborative decision making. The AATT terminal tools incorporate sophisticated logic that represent the performance characteristics of aircraft and propulsion systems and emulate flight management system (FMS) trajectory control characteristics. The DSTs' internal logic generate climb, descent and speed profiles, routings and schedules that are reasonably flight cost-efficient. Operating efficiency would further be enhanced through data exchange of user preferred trajectories (UPTs), aircraft capabilities and current and planned flight status, current meteorological measurements and forecasts, fleet prioritization information, schedule updates, and projected restrictions and delays. The information exchange would be supported by data link among ATM, flight deck and AOC components. Future tool enhancements will adaptively assimilate the exchanged data to develop operating solutions that are compatible, to the extent possible, with user preferences. Collaborative decision making between ATM and users would further improve ATM conformance with user optimization objectives and allow users to adapt in real-time to ATM constraints.

Integrated Arrival, Departure And En Route Operations

The DSTs are designed to maximize air traffic operating efficiency in their airport and airspace coverage domain. The domain could be an extended terminal area with single or multiple airports supported by single or multiple en route centers, or a network of terminal areas and supporting centers. The DSTs will develop schedule and trajectory plans that optimize the arrival and departure operation at individual airports or among a network of airports in accordance with user preferences, operational constraints, and known or projected traffic and meteorological conditions. Factors addressed by the DSTs include runway balancing (i.e., optimal runway assignments to minimize delay), optimum aircraft sequencing, and satellite airport arrival and departures. These terminal operating plans would be developed in coordination with en route operations to provide safe and efficient utilization of airports and airspace and lessen disruptions to planned schedules and flight times. The result would be increased throughput, reduced delay, and better utilization of the air traffic system.

Other Factors

The overall ability of the AATT DSTs to implement more efficient trajectories, sequences and schedules with more accurate control would produce beneficial impacts on safety, access, noise and emissions, and controller and pilot productivity. Improved trajectory control and prediction would reduce the likelihood of airspace incursions and flight technical errors, and would facilitate interventions where needed. Improved throughput and scheduling would enhance general access to airports, airspace and air traffic services. The increased use of optimized trajectories with reduced delays would lessen noise exposure and the quantity of emitted pollutants. Automated advisories and plans generated by the tools would assist controllers and pilots in their decision making and implementation processes.

Performance Metrics

Table 8-2 provide a summary of the relationships among DST functions, operational improvements and potential benefits impact, and identifies applicable economic and performance metrics.

Table 8-2 DST Operational Impacts and Metrics

DST Function	Operational Improvement	Benefit Impact	Metric
TMA - Traffic Management Advisor			
Display of delay absorption advisories to Center controllers to achieve metering fix crossing time schedules for arrival aircraft based on an optimized runway operating schedule	Reduced trajectory uncertainty at the arrival metering fix Reduced extraneous gaps at the landing runway Reduced spacing buffer at the runway threshold Improved runway system utilization	Reduced arrival flight delay due to runway system operations Reduced emissions Reduced noise exposure	Flight operating cost Flight delay Runway throughput Aircraft spacing Schedule adherence rating Noxious emissions quantity Noise exposure rating
Adjustment of the metering fix crossing time schedule to optimize delay distribution between Center and TRACON airspace	More fuel-efficient arrival flight trajectories	Reduced fuel burn Reduced emissions Reduced noise exposure	Flight operating cost Noxious emissions quantity Noise exposure rating

Table 8-2 DST Operational Impacts and Metrics (continued)

DST Function	Operational Improvement	Benefit Impact	Metric
Multi-Center TMA			
Same as TMA, with coordination of inbound flows from different Centers	Same as TMA	Same as TMA	Same as TMA

DST Function	Operational Improvement	Benefit Impact	Metric
pFAST - Passive Final Approach Spacing Tool			
Display of landing sequence advisories to TRACON controllers for arrival aircraft based on an optimized runway operating schedule	Reduced trajectory uncertainty at final approach and the runway threshold Reduced spacing buffer at the runway threshold Improved runway system utilization	Reduced arrival flight delay due to runway system operations Reduced emissions Reduced noise exposure	Flight operating cost Flight delay Runway throughput Aircraft spacing Schedule adherence rating Noxious emissions quantity Noise exposure rating
aFAST - Active Final Approach Spacing Tool			
Display of descent trajectory maneuver and landing sequence advisories to TRACON controllers for arrival aircraft based on an optimized runway operating schedule	Reduced trajectory uncertainty in TRACON airspace and at the runway threshold Reduced spacing buffer along trajectories and at the runway threshold Improved runway system utilization	Reduced arrival flight delay due to runway system operations Reduced emissions Reduced noise exposure	Flight operating cost Flight delay Runway throughput Aircraft spacing Schedule adherence rating Noxious emissions quantity Noise exposure rating

Table 8-2 DST Operational Impacts and Metrics (continued)

DST Function	Operational Improvement	Benefit Impact	Metric
CAP - Collaborative Arrival Planning			
One-way data exchange with transmittal of TMA data and display to AOC dispatchers of projected arrival times, delays, and fix traffic loadings	Improved AOC arrival-departure coordination decisions to accommodate connections Improved AOC decisions concerning flight diversion to alternate airport for delayed arrivals Improved AOC allocation of airline resources, including aircraft, gate, ramps, flight and ground crews, baggage routing, and support equipment Improved AOC resolutions of irregularities in response to flight schedule disruption projections Improved fleet-wide flight planning and arrival fix loading	Reduced arrival and departure delays due to resource allocation decisions Reduced misconnections for aircraft, passengers, baggage and crew Reduced avoidable arrival flight diversions and earlier unavoidable arrival flight diversions Reduced cancellations Reduced baggage induced delays	Flight operating cost Ground operations personnel cost Flight delay Schedule adherence rating Flight airport diversion rate Flight, passenger and baggage misconnection rates Flight and passenger cancellation rates Low-fuel landing rate
Two-way data exchange with transmittal of AOC data to ATM automation describing user preferences, flight plan and schedule updates, and aircraft status for arrival flights	Improved conformance of DST sequencing of arrivals with user preference Improved conformance of DST delay absorption planning with user preference	Reduced delays Reduced misconnections for aircraft, passengers, baggage and crew Reduced flight diversions Reduced cancellations	Flight operating cost Flight delay Schedule adherence rating Flight airport diversion rate Flight mis-connection rate Flight cancellation rate

Table 8-2 DST Operational Impacts and Metrics (concluded)

DST Function	Operational Improvement	Benefit Impact	Metric
EDP - Expedite Departure Path			
Display of ascent trajectory maneuver and departure fix sequence advisories to TRACON controllers for departure flights based on an integrated airport and airspace system operating plan	Reduced trajectory uncertainty in TRACON airspace and at the departure fix Reduced spacing buffer along trajectories Reduced interruptions to user preferred climb profiles due to procedures or potential conflicts Improved runway and airspace system utilization	Reduced arrival and departure flight delay due to runway system operations Reduced diversion from optimum climb profiles Reduced emissions Reduced noise exposure	Flight operating cost Flight delay Runway throughput Aircraft spacing Schedule adherence rating Noxious emissions quantity Noise exposure rating
Provision of data to support display of optimum departure release times at primary and satellite airports	Reduced interruptions to user preferred flight schedules Reduced manual coordination among TRACON/Tower controllers	Reduced departure flight delay due to airspace acceptance constraints Reduced emissions Reduced noise exposure	Flight operating cost Flight delay Runway throughput Aircraft spacing Schedule adherence rating Noxious emissions quantity Noise exposure rating

Analysis Process

Seagull has developed a methodology for evaluating DST performance and impacts on air traffic operations. The methodology is designed to examine improved aircraft trajectory control prediction and accuracy, improved knowledge of user preferences, and improved flight planning and scheduling flexibility, and determine the resulting impacts on aircraft operating costs and various performance metrics. As part of this methodology, Seagull has developed, and continues to develop, a analytical formulations, computer-based modelings and engineering analysis to represent the DST-based improvements and quantify their impacts. The process focuses on capturing the salient operational features and nuances of the DSTs by modeling the purpose and intent of the DST algorithmic logic and accounting for procedural constraints and the capabilities of supporting technologies, such as advanced FMS, high-fidelity data link, and global position system (GPS) services.

The analysis process is schematically depicted in Figure 8-4. This analysis process:

- Identifies the operating characteristics of DSTs and supporting technologies;
- Determines the sensitivity of various trajectory accuracy parameters to the use of the AATT DSTs and supporting technologies;

- Evaluates the resulting improved capability of the ATM system to predict and control trajectories;
- Evaluates delay, delay distribution, trajectory and scheduling impacts on flight operations, costs and performance metrics for the airport and airspace system using analytical formulations, computer-based modeling and engineering analysis logic; and
- Assesses the associated aircraft operating cost savings and other pertinent metrics

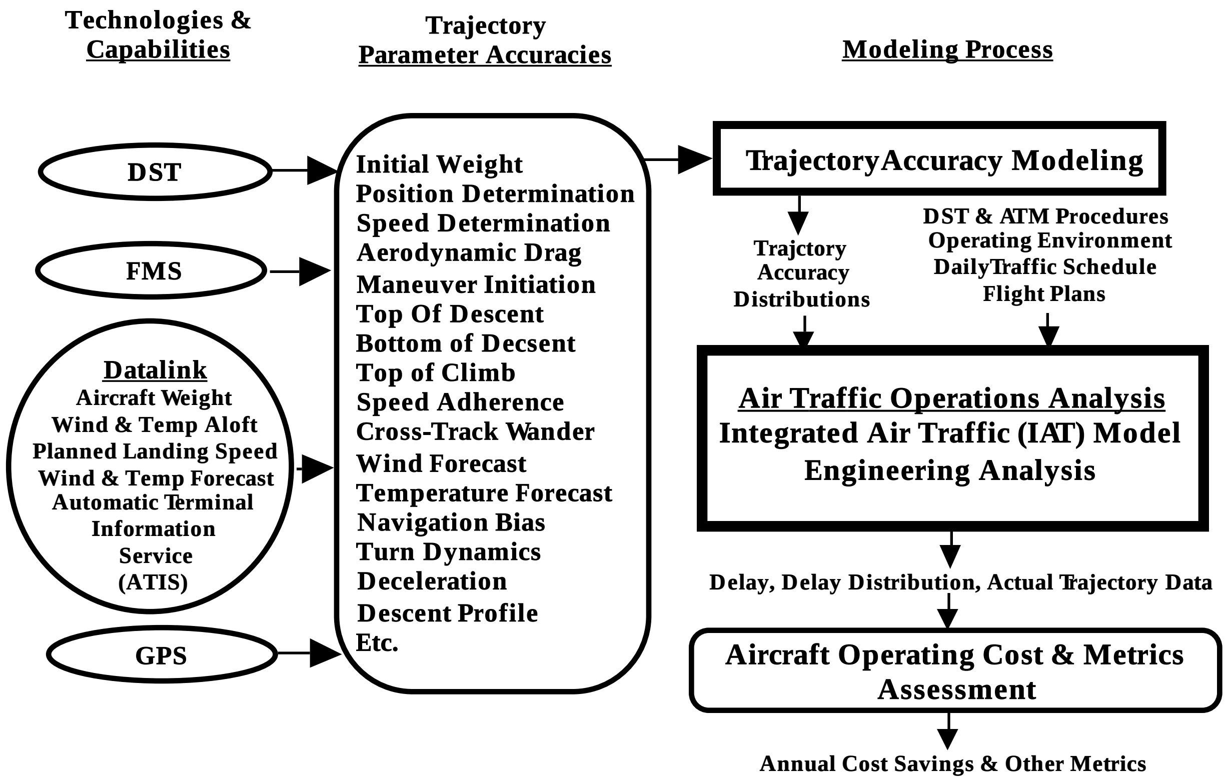


Figure 8-4 Analysis Process

The following summarizes the analysis process steps:

Technologies and Capabilities Identification

The analysis process is initiated by identifying the subject DST and supporting technologies, and defining the associated operating capabilities in terms of functional, technical and performance characteristics and requirements. The technologies and capabilities, such as those identified in Figure 8-4, would include ATM, flight management, communication, navigation, surveillance, and meteorological components. The technologies and capabilities identification process normally also is performed for the current ATM system to provide a commonly accepted and familiar baseline for comparison.

Trajectory Parameter Accuracies and Distributions Determination

The process describes DST and supporting technologies in terms of parameters that affect aircraft trajectory prediction and control accuracy. These parameters cover aircraft performance, maneuver actuation, atmospheric, and surveillance categories. Key parameters typically impacted by DSTs and supporting technologies are listed in Figure 8-4. Each parameter is quantitatively defined by a stochastic distribution (e.g., mean and standard deviation of a truncated Gaussian probability density function) representing the contribution of that parameter to trajectory errors. These trajectory error parameter distributions are evaluated for current and DST operations based on engineering analysis and mathematical modeling, often with reliance on published data describing technical performance. The parameter stochastic effects on aircraft track controllability are the subject of trajectory accuracy modeling.

Trajectory Accuracy Modeling

The accuracy with which a trajectory can be predicted and controlled has been modeled using computer simulation, closed-form analytical solutions, and a combination of the two, as appropriate, for climb, cruise and descent operations. [ref.22] The individual parameter accuracy distributions of the preceding step are inputs to this trajectory dynamics modeling. The outputs are fix crossing delivery accuracies for current, DSTs and supporting technologies. This accuracy is a stochastic distribution, typically defined by the standard deviation of a zero-mean probability function.

A key analysis tool in this trajectory modeling process is a high-fidelity fast-time computerized replication of a flight trajectory developed by Seagull. This simulation model, named Amelia, is used in conjunction with Monte Carlo modeling to analyze aircraft movement along a flight path. Amelia generates a trajectory in response to maneuver commands for various aircraft. It has adjustable parameters describing aircraft flight performance and environmental characteristics. These modeling parameters are adjusted stochastically to enable analysis of the factors contributing to variance between actual and intended trajectories. The simulation is applied to flight segments to examine trajectory prediction, surveillance, and pilotage accuracies defined by the trajectory error parameter inputs. The modeling enables determination of crossing time delivery accuracies at various points such as the metering fix, outer marker, runway threshold, and departure fix illustrated in Figure 8-5.

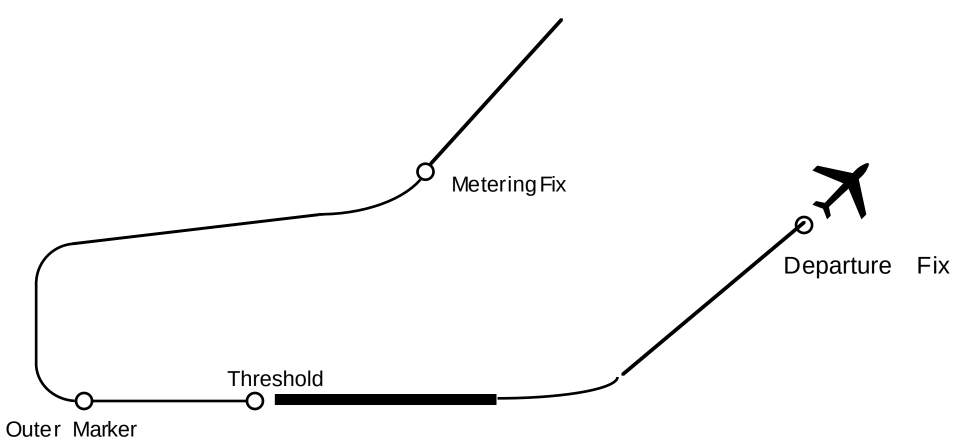


Figure 8-5 Trajectory Accuracy Modeling System

Seagull also has used the results of Center-TRACON Automation System (CTAS) prototype field tests to examine trajectory accuracy. [ref.15] The field test data include observed metering fix crossing time delivery accuracies and runway threshold interarrival separations. CTAS currently includes TMA and pFAST, but various CTAS builds will include additional DSTs.

Airport and Airspace Analysis

The analysis process allows quantitative and qualitative evaluations of DST operations and potential benefits impacts. Modeling and engineering analysis may be used for quantitative evaluations of capacity, flexibility, and predictability performance metrics and associated economic factors. Engineering logical and statistical analysis may be used to support and develop qualitative evaluations of safety, access, and environmental performance metrics. Modeling and engineering analysis are described in the following paragraphs.

Integrated Air Traffic (IAT) Model -- The IAT Model is a new high-fidelity computerized simulation model specifically designed for quantitative evaluations of Free Flight and AATT DST performance characteristics, as well as current operations. Seagull independently is developing this advanced trajectory-based airport and airspace capacity and delay model to enable representation of ATM operations and user preferences in constrained and unconstrained air traffic environments. The IAT Model simulates and evaluates DST impacts on aircraft operations with respect to flight delay, diversion, scheduling and planning. The role of the IAT Model in the DST benefits analysis process is shown in Figure 8-6.

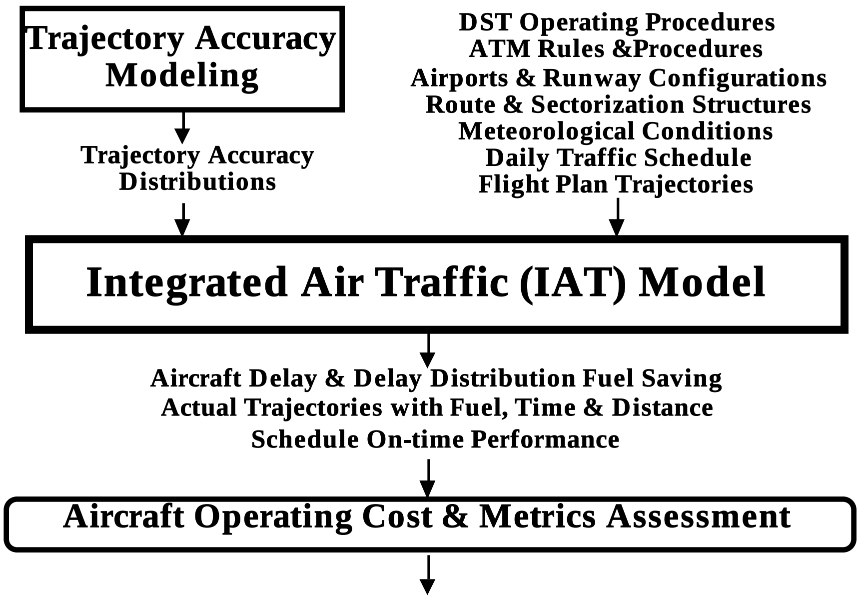


Figure 8-6 Integrated Air Traffic (IAT) Model Application

The IAT Model has an object oriented design uniquely configured to be adaptable to alternative ATM, AOC, and flight operating regimes. The IAT Model is a fast-time computerized simulation that replicates the movement of individual aircraft through airport and airspace segments to assess capacity, delay, aircraft performance and operating cost relationships. The model processes data defining traffic demand, runway system configuration, airport and airspace operating procedures, and trajectory prediction and control accuracy, and examines DST impacts on aircraft operations with respect to flight delay, diversion, scheduling and planning. The model logic accounts for inter-aircraft spacings, and distinguishes the impacts on delay of the different trajectory control capabilities associated with the proposed tools as well as current operations. The model accounts for trajectory dynamics, delay distribution, interactions among multiple trajectories, trajectory optimization, and flight schedule.

The fully-implemented model would track each aircraft to or from an airport terminal gate and through the runway system and terminal and en route transition and cruise airspace. This IAT Model would be applicable to a single airport, multiple airports in terminal area, or a network of airports. The IAT Model in this study is composed of integrated modules pertinent to terminal airspace DSTs serving a major airport, and includes the following capabilities:

- Flight Scheduling And Trajectory Planning -- The initial schedule and trajectory plan for each arrival and departure flight and overflight are encoded and rescheduling and replanning are processed during the simulation.
- Runway System Modeling -- Runway system utilization is simulated, taking into account integration with airspace trajectory and surface movement operations; key factors are the runway configuration, aircraft separation procedures, runway assignment procedures, and logic meteorological factors.
- Airspace Trajectories Modeling -- The movement of each aircraft is simulated according to requested, assigned and reassigned trajectories, planned and actual fix crossing schedules based on delivery time accuracy, aircraft separation procedures and buffers, airspace restrictions, and meteorological factors; the simulation logic is being developed to enable depiction of various DST functionalities, such as delay distribution, runway balancing, optimized arrival and departure sequencing, improved arrival, departure and en route trajectory assignment, and improved potential conflict intervention tactics.

The IAT Model uses Monte Carlo techniques to support stochastic assessment of schedule planning, trajectory assignment, sequencing, spacing, and trajectory delivery accuracy at fixes and runway thresholds. IAT Model results include quantitative estimates of aircraft daily delays and diversions from preferred trajectories and schedules for the airports and airspace domain under study.

Engineering Analysis -- Engineering analysis is appropriate for either quantitative or qualitative evaluation of parameters depending on analytical requirements. Engineering analysis is applicable where available data are insufficient to support the IAT Model, where such sophisticated modeling is not warranted, or the where the evaluation is beyond the intended scope of the IAT Model. Although any quantitative analysis in this study should be comparable in veracity with that of the IAT Model, consideration of the information and resources available require that engineering analysis be applied to develop numeric as well as subjective evaluations of potential benefits where appropriate. Statistical and logical engineering analyses are useful in identifying the likely consequence of an impact, positive or negative, and order of magnitude.

Engineering analysis is applicable in general to qualitative evaluations of safety, access and environmental performance metrics, and to quantitative evaluations of system flexibility. In these evaluations, the relevant operational improvements enabled by the deployment of the DSTs are identified. The results are used as a basis to define the affected performance metrics and determine the degree of significance of the impact on each metric. These determinations are based on logical constructions of the causative relationships among DST functions, operational improvements and benefits impacts, supported by statistical data. For example, statistical examination of archived data and logical assessment are applicable to determinations of impacts on user operations due to ATM-AOC data exchange associated with the CAP DST. Seagull and American Airlines are exploring studies of airline data and AOC preference strategies that would apply statistical analysis and simplified computerized modeling routines to identify and rate the relative degree of DST impacts.

Also, IAT modeling is helpful in establishing the likelihood of significant impact on metrics relating to reduced fuel consumption, reduced aircraft emissions, and reduced noise exposure. The IAT Model results define flight trajectory impacts due to the DST under evaluation. These results describe fuel burn and enable assessment of trends relating to aircraft emissions and noise exposure.

Aircraft Operating Cost and Metrics Assessment

A set of computerized analytical routines is used to convert and extrapolate daily traffic delay metrics to annual and national cost impacts. Cost estimation and extrapolation parameters include aircraft operating cost, annual traffic demand and meteorological factors. Special analyses may be performed to examine the sensitivity of the estimated annual cost savings to perturbations in parameters and assumptions.

Methodologies for evaluating metrics are identified in Table 8-3. Table 8-3 lists various performance metrics and specifies the corresponding evaluation methodology based on the discussions in the preceding paragraphs.

Table 8-3 Performance Metrics Evaluation Methods - Preliminary

Metric Category	Metric	Evaluation Methodology	Evaluation Type	Subject DST
Capacity	Flight operating cost	IAT Model	Quantitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP
Capacity	Flight delay	IAT Model	Quantitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP
Capacity	Runway system throughput	IAT Model	Quantitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP
Capacity	Aircraft spacing	IAT Model	Quantitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP
Predictability	Schedule adherence rating	IAT Model	Quantitative	TMA, Multi-Center TMA, aFAST, pFAST, CAP, EDP
Flexibility	Flight airport diversion rate	Engineering analysis	Quantitative	CAP
Safety	Low-fuel landing rate	Engineering analysis	Qualitative	CAP
Access	Flight, passenger and baggage misconnection rates	Engineering analysis	Qualitative	CAP
Access	Flight and passenger cancellation rates	Engineering analysis	Qualitative	CAP
Environment	Noxious emissions quantity	Engineering analysis	Qualitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP
Environment	Noise exposure rating	Engineering analysis	Qualitative	TMA, Multi-Center TMA, aFAST, pFAST, EDP

Additional metrics may provide supplementary explanatory insights into the DST benefits impacts. Table 8-4 lists auxiliary metrics that may be evaluated quantitatively for TMA, Multi-Center TMA, aFAST, pFAST, CAP, and EDP operations.

Table 8-4 Auxiliary Performance Metrics - Preliminary Candidates

Auxiliary Metric

Capacity

Flight time

Flight distance

Maximum runway system throughput rate during traffic rush

Runway system landing versus takeoff operating rate

Maximum instantaneous aircraft count in specified airspace segments

Excess spacing at runway thresholds, metering fix, departure fix and outer arc

Difference between DST-planned and actual crossings of runway thresholds, metering fix, and departure fix

Differences between scheduled, DST-planned and actual crossings of runway thresholds, metering fix, and departure fix

Predictability

Flight fuel consumption variance distribution

Flight time variance distribution

Time duration at non-optimum altitude variance distribution

Time duration on non-optimum route variance distribution

Flight distance variance distribution

Distance flown at non-optimum altitude variance distribution

Distance flown on non-optimum route segment variance distribution

Runway system throughput rate during traffic rush variance distribution

Runway system landing versus takeoff operating rate variance distribution

Number of runway reassignments variance distribution

Number of resequences variance distribution

Maximum instantaneous aircraft count in specified airspace segments variance distribution

Variance distribution of excess spacing at runway thresholds, metering fix, departure fix and outer arc

Variance distribution of differences between scheduled, DST-planned and actual crossings of runway thresholds, metering fix, and departure fix

Flexibility

Time duration at diverted altitude

Time duration on diverted route

Distance flown at diverted altitude

Distance flown on diverted route segment

Table 8-4 Auxiliary Performance Metrics - Preliminary Candidates (concluded)

<u>Safety</u>

Number of runway reassignments

Number of resequences

Number of trajectory interventions

<u>Access</u>

Runway system non-busy time duration distribution

<u>Environment</u>

Flight fuel consumption

Flight duration at lower altitudes

9. Modeling of DST Benefits

The IAT Model evaluates traffic demand, capacity, delay and diversion relationships among flights based on scheduled departure and arrival times. The trajectory of each flight in a traffic demand specification for a subject airport is modeled. This demand may be a daily schedule of arrivals and departures, and may include flights to and from nearby local airports and overflights. The model processes a planned trajectory through the airspace and airport runway system, and generates trajectory interventions in accordance with air traffic control and flight operating procedures and rules.

The scheduled takeoff and landing times for each flight may be pre-specified, or calculated by adjusting a scheduled gate departure or arrival time to account for taxiing. Actual takeoff, landing and airspace fix crossing times and trajectory delays and diversions are determined by simulating the interactions of the flight schedule and associated requested trajectories, flight performance characteristics, airspace operating rules, runway system operating configurations and associated arrival and departure procedures, and the appropriate aircraft separation procedures corresponding to visual flight rules (VFR) and instrument flight rules (IFR). A combination of visual meteorological conditions (VMC) and instrument meteorological conditions (IMC) may be specified by time of day, with runway configurations and airspace procedures adjusted accordingly.

The modeling process tabulates: delay to departure flights, taken on the ground at an airport or during ascent and outbound cruise; delay to arrival flights, taken during inbound cruise or descent to an airport; and delay to overflights, taken in en route or terminal airspace. The model also records trajectory assignments, which include diversions.

Modeling parameters describing operating procedures are adjusted to enable comparison of current and DST systems. The model is applied to scenarios representing VFR and IFR operations at 10 selected airports using a daily traffic sample. These airports are representative of those that could be sites for DST implementation, and are:

DEN	Denver International Airport
DFW	Dallas-Ft. Worth International Airport
EWR	Newark International Airport
JFK	New York John F. Kennedy International Airport
LAX	Los Angeles International Airport
LGA	New York LaGuardia Airport
MSP	Minneapolis-St. Paul International Airport
ORD	Chicago O'Hare International Airport
PHL	Philadelphia International Airport
SFO	San Francisco International Airport

Traffic Data

Traffic demand data describing flight trajectories for selected sample days in the years 1996 and 2015 are provided by NASA.[ref.31] The daily traffic samples for 1996 are derived from FAA radar track and flight plan data for active flights for the entire domestic US airspace. These data are adjusted to construct trajectories that represent user flight plans for 1996 and future years. The sample includes commercial, general aviation, and military flights, and accounts for domestic flights and international flights with origins or destinations in the US. The trajectory traffic sample for

Friday, June 14, 1996, represents a relatively busy day and is selected for use in his study. The corresponding sample day trajectory data for 2015 are based on FAA traffic forecasts.[ref.32]

The traffic data for each flight defines a scheduled trajectory. The data specifies a unique flight identification, aircraft equipment type, origin and destination airport, and scheduled runway wheels-off and wheels-on times, route of flight, altitude profile and airspace fix crossing times.

Separate traffic data samples are provided for a selected day to represent various operating assumptions. A traffic sample may describe one of the following:

1. Trajectories based on recorded flight plan and actual flight path data, with the entire cruise at the filed initial flight level in accordance with current standard hemispherical flight direction and vertical separation rules (i.e., 2000 ft altitude separation above flight level 290).
2. Trajectories for wind optimized routes, with the entire cruise at the filed initial flight level in accordance with current standard hemispherical flight direction and vertical separation rules.
3. Trajectories for wind optimized routes, with the entire cruise at the flight level that is nearest the filed initial flight level but in accordance with Reduced Vertical Separation Minima (RVSM) rules (i.e., 1000 ft altitude separation).
4. Trajectories for wind optimized routes and step climb profiles using current standard hemispherical flight direction and vertical separation rules.
5. Trajectories for wind optimized routes and step climb profiles using RVSM flight levels.
6. Trajectories for wind optimized routes and cruise climb profiles.

The trajectories are constructed[ref.31] by flight plan modeling assuming a 0.7 load factor, 250 pounds per passenger, and a 45-minute reserve. Wind optimization is applied only to domestic flights greater than 1000 nmi and cruising above 15000 feet.

Traffic sample type 4, trajectories on wind optimized routes and step climb profiles using standard hemispherical flight levels, represents current operations and is selected for use in this study to analyze 1996 potential benefits impacts. RVSM currently is being considered for implementation, in which case RVSM would be in operation in 2015. Hence, traffic sample type 5, trajectories on wind optimized routes and step climb profiles using RVSM flight levels, is selected for use in this study to analyze 2015 potential benefits impacts. Analyses based on these two sample types, as well as others, in both study years would be of value but are not performed because study resources limit modeling applications.

Aircraft Class

The equipage information enables categorization of each flight according to its aircraft class. This aircraft class data item provides a basis for evaluating operating costs that are sensitive to aircraft performance characteristics. An aircraft class is a group of aircraft types, in which each type has similar performance and operating cost characteristics. A means of defining classes is to categorize each aircraft type according to the number of engines, type of engine, and aircraft size, as shown in Table 9-1.

Table 9-1 Aircraft Class Descriptors

Number Of Engines	Engine Type	Size Type
1, 2, 3, or 4	J = jet	H = heavy
	T = turboprop	LH = large-to-heavy
	P = piston	L = large
		LS = large-to-small
		S+ = small-to-large
		S = small

Table 9-2 lists aircraft classes exemplifying those in the traffic demand data, with representative aircraft types for each class. A comprehensive tabulation of aircraft types by class can be found in Appendix A. For this study, the size definition and designation are modified from that of a published standard (e.g., as applied in the FAA's Air Traffic Control Handbook [ref.33]) so as to distinguish operating costs rather than air traffic control separation requirements or runway and taxiway loading. However, the size definitions of the FAA Handbook are used as a basic guideline. The FAA Handbook definitions are:

- Heavy -- aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight.
- Large -- aircraft of more than 41,000 pounds, maximum certified takeoff weight, up to 255,000 pounds.
- Small -- Aircraft of 41,000 pounds or less maximum certified takeoff weight, where: S+ denotes aircraft weighing between 12,500 and 41,000 pounds

The use of the non-standard large-to-heavy (LH) and large-to-small (LS) categories enables distinction among different size 2-engine jet aircraft such as the Boeing 757 (LH), McDonnell-Douglas MD-80 (L), Boeing 737 (L) and Fokker 100 (LS), which otherwise would all be designated as large (L). Engine Type/Size Type-only designators are applied to aircraft whose engine count is not determinable in the traffic database. The supersonic transport (SST) is designated as a unique class, regardless of engine and size characteristics.

Daily Traffic Sample

The flight composition of the 1996 and 2015 daily traffic samples are summarized by aircraft class in Tables 9-3 and 9-4 for each of the airports under study. These data show that the number of daily operations, takeoffs and landings, range among the subject airports from 859 (at JFK) to 2164 (at DFW) in 1996 and 997 (at JFK) to 3246 (at DFW) in 2015. Tables 4-5 and 4-6 show the percentage distribution of the daily traffic by aircraft class for each airport. Two-engine large jet predominate in 1996; two-engine large and large-to-heavy jet and two-engine turboprop aircraft predominate in 2015.

Table 9-2 Aircraft Classes and Representative Aircraft Types

Eng. Type	Eng. Num	A/C Size	Aircraft Class	Representative Aircraft Type	Representative Aircraft Type Description
J	4	H	4J/H	B74A,B74B	Boeing Co. 747-100/200/300, 747-400
			4J/H	A340	Airbus Industries A340
			4J/H	B707	Boeing Co. 707 (all series)
J	4	L	4J/L	BA46	British Aerospace BAe 146
			4J/L	DC8	McDnl-Dgls DC-8 (all series)
J	3	H	3J/H	L101	Lockheed Corp L-1011 Tri-star (all series)
			3J/H	DC10	McDnl-Dgls DC-10
			3J/H	MD11	McDnl-Dgls MD-11
J	3	L	3J/L	B727	Boeing Co. 727 (all series)
J	2	H	2J/H	B767	Boeing Co. 767 (all series)
			2J/H	B777	Boeing Co. 777
			2J/H	A300, 310, 330	Airbus Industries A300, A310, A330
J	2	LH	2J/LH	B757	Boeing Co. 757 (all series)
			2J/LH	A320	Airbus Industries A320
J	2	L	2J/L	B73A,B73B	Boeing Co. 737/200. 737-300/400/500
			2J/L	DC9,MD80	McDnl-Dgls DC-9 Super/MD-80 series
J		L	J/L	NA	jet (400 kts and above), large, 32,000' and above
J	2	LS	2J/LS	F100, F28	Fokker BV Fokker 1OO, Fellowship F28
J	2	S+	2J/S+	FA01	Dassault-Breguet Falcon 10
			2J/S+	LJ24	Gates Learjet Corp Learjet 24
J		S+	J/S+	NA	jet (400 kts and above), small+, 0 – 31,900' alt
J	2	S	2J/S	LJ23	Gates Learjet Corp Learjet 23
T	4	L	4T/L	DHC7	DeHavilland DASH 7 DHC-7
			4T/L	L188	Lockheed Corp, Electra 188/Orion P3
T	2	L	2T/L	ATR	Aerospatiale/Aeritalia, ATR 72
			2T/L	DHC8	DeHavilland DASH 8 DHC-8
			2T/L	FK7	Fokker BV, Friendship F27
T	2	S+	2T/S+	B190	Beech Aircraft, 1900
			2T/S+	JTSA	British Aerospace BAe Jetstream 31
			2T/S+	E120	Embraer Brasilia EMB-120
			2T/S+	SH33	Short Brothers Ltd. Shorts 330
T		S+	T/S+	NA	turboprop(279–399kts),small+,25,100'– 34,900'alt
T	2	S	2T/S	BE99	Beech Aircraft, Airliner 99
			2T/S	SW4	Fairchild(Swearingen)Metro 4
			2T/S	DHC6	DeHavilland Twin Otter DHC-6 (all series)
			2T/S	E110	Embraer Bandeirante EMB-110/111
T	1	S	1T/S	DH2T	DeHavilland, DHC-2T Turbo-Beaver
P	4	L	4P/L	DC6	McDnl-Dgls DC-6/B Liftmaster
			4P/L	CONI	Lockheed Corp, Constellation,Super Constellation
P	2	L	2P/L	CVLP	General Dynamics Corp. Convair 240/340/440
P	2	S+	2P/S+	DC3	McDnl-Dgls DC-3 (all series)
			2P/S+	G21, G73	Grumman Aerospace Goose/Super Goose, Mallard
P	2	S	2P/S	BE50	Beech Aircraft, Twin Bonanza 50
			2P/S	C303	Cessna Aircraft, Crusader 303
			2P/S	PA30	Piper Aircraft, Twin Comanche
P	1	S	1P/S	DHC2, DHC3	DeHavilland DHC-2 Beaver, DHC-3 Otter
J	4	H	SST	CONC	Aerospatiale/British Aerospace Concorde

Table 9-3 1996 Sample Daily Traffic Count by Airport

A/C Class:	DEN	DFW	EWR	JFK	LAX	LGA	MSP	ORD	PHL	SFO
	Traffic Count (Number of Daily Operations)									
4J/H	8	13	9	49	28	0	8	32	16	35
4J/L	41	3	9	7	23	0	8	43	7	12
3J/H	30	27	25	37	87	3	27	36	2	34
3J/L	154	166	139	66	78	164	129	230	61	41
3J/S+	0	0	0	0	1	0	0	2	3	1
2J/H	19	33	27	127	88	2	2	44	12	47
2J/LH	138	121	105	44	193	74	133	182	65	155
2J/L	406	700	418	57	577	316	403	818	346	462
J/L	0	0	0	0	0	0	0	0	0	1
2J/LS	0	109	12	0	3	25	28	109	26	4
2J/S+	29	9	34	25	21	8	42	12	32	19
2J/S	0	2	0	0	0	0	0	2	0	0
4T/L	0	2	0	1	0	0	4	2	11	0
2T/L	17	479	146	187	73	128	110	243	112	0
2T/S+	243	145	89	128	538	100	170	86	155	167
2T/S	21	4	1	4	5	3	19	9	6	10
1T/S	3	14	3	1	10	0	2	4	0	3
4P/L	0	0	0	0	0	0	0	0	0	0
2P/L	1	0	0	0	0	0	0	0	0	0
2P/S+	0	0	0	0	0	0	1	0	0	0
P/S+	81	295	121	105	188	63	96	274	71	96
2P/S	15	17	1	6	1	2	30	14	12	9
P/S	7	23	30	10	27	37	15	10	32	1
1P/S	0	2	1	1	2	2	2	0	5	2
SST	0	0	0	4	0	0	0	0	0	0
ALL	1213	2164	1170	859	1943	927	1229	2152	974	1099

Table 9-4 2015 Sample Daily Traffic Count by Airport

A/C	Traffic Count (Number of Daily Operations)									
Class:	DEN	DFW	EWR	JFK	LAX	LGA	MSP	ORD	PHL	SFO
4J/H	1	8	14	43	39	0	2	21	8	37
4J/L	31	46	31	15	35	13	25	65	25	39
3J/H	5	20	20	20	22	4	7	18	6	20
3J/L	0	0	0	3	3	0	0	0	2	1
3J/S+	0	0	0	0	1	0	0	2	3	0
2J/H	86	150	102	134	103	36	74	176	68	121
2J/LH	318	642	335	144	451	158	293	491	215	458
2J/L	685	1177	618	170	651	494	722	1195	493	541
J/L	56	116	67	24	98	74	85	142	60	88
2J/LS	44	48	43	5	22	32	38	99	42	27
2J/S+	25	9	26	24	17	8	44	9	30	18
2J/S	0	2	0	0	0	0	0	2	0	0
4T/L	5	8	3	7	2	0	6	1	0	0
2T/L	167	559	210	178	408	155	186	187	217	148
2T/S+	132	337	120	142	237	104	143	166	159	85
2T/S	15	22	15	14	18	5	31	18	20	19
1T/S	0	0	0	0	0	0	0	0	0	0
4P/L	0	1	0	1	0	0	1	0	0	0
2P/L	1	0	0	0	0	0	0	0	0	0
2P/S+	0	0	0	0	0	0	0	0	0	0
P/S+	0	0	1	1	0	0	0	0	3	0
2P/S	10	17	5	17	18	5	31	32	17	15
P/S	32	82	36	48	85	26	33	47	47	40
1P/S	0	2	1	6	1	3	2	0	5	2
SST	0	0	0	1	0	0	0	0	0	0
ALL	1613	3246	1647	997	2211	1117	1723	2671	1420	1659

Table 9-5 1996 Sample Daily Traffic Distribution by Airport

A/C Class:	Traffic Count (Percent of Daily Operations) DEN	DFW	EWR	JFK	LAX	LGA	MSP	ORD	PHL	SFO
4J/H	0.7%	0.6%	0.8%	5.7%	1.4%	0.0%	0.7%	1.5%	1.6%	3.2%
4J/L	3.4%	0.1%	0.8%	0.8%	1.2%	0.0%	0.7%	2.0%	0.7%	1.1%
3J/H	2.5%	1.2%	2.1%	4.3%	4.5%	0.3%	2.2%	1.7%	0.2%	3.1%
3J/L	12.7%	7.7%	11.9%	7.7%	4.0%	17.7%	10.5%	10.7%	6.3%	3.7%
3J/S+	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.3%	0.1%
2J/H	1.6%	1.5%	2.3%	14.8%	4.5%	0.2%	0.2%	2.0%	1.2%	4.3%
2J/LH	11.4%	5.6%	9.0%	5.1%	9.9%	8.0%	10.8%	8.5%	6.7%	14.1%
2J/L	33.5%	32.3%	35.7%	6.6%	29.7%	34.1%	32.8%	38.0%	35.5%	42.0%
J/L	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
2J/LS	0.0%	5.0%	1.0%	0.0%	0.2%	2.7%	2.3%	5.1%	2.7%	0.4%
2J/S+	2.4%	0.4%	2.9%	2.9%	1.1%	0.9%	3.4%	0.6%	3.3%	1.7%
2J/S	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
4T/L	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%	0.3%	0.1%	1.1%	0.0%
2T/L	1.4%	22.1%	12.5%	21.8%	3.8%	13.8%	9.0%	11.3%	11.5%	0.0%
2T/S+	20.0%	6.7%	7.6%	14.9%	27.7%	10.8%	13.8%	4.0%	15.9%	15.2%
2T/S	1.7%	0.2%	0.1%	0.5%	0.3%	0.3%	1.5%	0.4%	0.6%	0.9%
1T/S	0.2%	0.6%	0.3%	0.1%	0.5%	0.0%	0.2%	0.2%	0.0%	0.3%
4P/L	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2P/L	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2P/S+	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
P/S+	6.7%	13.6%	10.3%	12.2%	9.7%	6.8%	7.8%	12.7%	7.3%	8.7%
2P/S	1.2%	0.8%	0.1%	0.7%	0.1%	0.2%	2.4%	0.7%	1.2%	0.8%
P/S	0.6%	1.1%	2.6%	1.2%	1.4%	4.0%	1.2%	0.5%	3.3%	0.1%
1P/S	0.0%	0.1%	0.1%	0.1%	0.1%	0.2%	0.2%	0.0%	0.5%	0.2%
SST	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
ALL	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 9-6 2015 Sample Daily Traffic Distribution by Airport

A/C Class:	Traffic Count (Percent of Daily Operations) DEN	DFW	EWR	JFK	LAX	LGA	MSP	ORD	PHL	SFO
4J/H	0.1%	0.2%	0.9%	4.3%	1.8%	0.0%	0.1%	0.8%	0.6%	2.2%
4J/L	1.9%	1.4%	1.9%	1.5%	1.6%	1.2%	1.5%	2.4%	1.8%	2.4%
3J/H	0.3%	0.6%	1.2%	2.0%	1.0%	0.4%	0.4%	0.7%	0.4%	1.2%
3J/L	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%
3J/S+	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.0%
2J/H	5.3%	4.6%	6.2%	13.4%	4.7%	3.2%	4.3%	6.6%	4.8%	7.3%
2J/LH	19.7%	19.8%	20.3%	14.4%	20.4%	14.1%	17.0%	18.4%	15.1%	27.6%
2J/L	42.5%	36.3%	37.5%	17.1%	29.4%	44.2%	41.9%	44.7%	34.7%	32.6%
J/L	3.5%	3.6%	4.1%	2.4%	4.4%	6.6%	4.9%	5.3%	4.2%	5.3%
2J/LS	2.7%	1.5%	2.6%	0.5%	1.0%	2.9%	2.2%	3.7%	3.0%	1.6%
2J/S+	1.5%	0.3%	1.6%	2.4%	0.8%	0.7%	2.6%	0.3%	2.1%	1.1%
2J/S	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
4T/L	0.3%	0.2%	0.2%	0.7%	0.1%	0.0%	0.3%	0.0%	0.0%	0.0%
2T/L	10.4%	17.2%	12.8%	17.9%	18.5%	13.9%	10.8%	7.0%	15.3%	8.9%
2T/S+	8.2%	10.4%	7.3%	14.2%	10.7%	9.3%	8.3%	6.2%	11.2%	5.1%
2T/S	0.9%	0.7%	0.9%	1.4%	0.8%	0.4%	1.8%	0.7%	1.4%	1.1%
1T/S	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
4P/L	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
2P/L	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2P/S+	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
P/S+	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%
2P/S	0.6%	0.5%	0.3%	1.7%	0.8%	0.4%	1.8%	1.2%	1.2%	0.9%
P/S	2.0%	2.5%	2.2%	4.8%	3.8%	2.3%	1.9%	1.8%	3.3%	2.4%
1P/S	0.0%	0.1%	0.1%	0.6%	0.0%	0.3%	0.1%	0.0%	0.4%	0.1%
SST	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
ALL	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Aircraft Operating Cost Rates

Estimated fuel and direct crew and maintenance costs per minute by aircraft class are listed in Table 9-7. These unit aircraft operating cost rates are based on FAA data and estimating procedures. [ref.34,35] The FAA data describe unit cost rates by individual aircraft type and by categories analogous to those used in this report. The FAA values are updated to 1996 dollars according to FAA-specified forecast consumer price index and fuel cost escalation factors. The crew, maintenance and airborne fuel cost rates are derived directly from the available FAA data. The ground fuel cost rates are based on informal estimates provided by airline personnel. The derivation of the aircraft operating cost rates is described in Appendix B.

This study analyzes aircraft delays by departures and arrivals. Departure delays are incurred on the airport by aircraft scheduled to takeoff, and arrival delays are incurred in flight by aircraft inbound to the airport. The ground fuel cost rate shown in Table 9-7 pertains to departure delay, and the airborne fuel cost rate pertains to arrival delay. The corresponding total aircraft operating cost rates applicable to departure and arrival delays for each class are listed as the final two columns of Table 9-7. Each of these are the sum of the crew and maintenance cost rates and the appropriate ground or airborne fuel and oil cost rate.

Aircraft operating cost rates that are representative of the airport-specific fleet mix are determined by weighting the unit cost rate for each aircraft class, shown in Table 9-7, according to each airport's aircraft class distribution, shown in Tables 9-5 and 9-6. The resulting average aircraft operating cost rates applicable to arrival and departure delays are shown in Table 9-8 for each airport under study and for 1996 and 2015 fleet mixes.

The cost rates shown in Tables 9-7 and 9-8 represent expenditures directly related to time spent in actual flight, while taxiing or waiting at idle. Maintenance cost represents the time contribution to engine overhaul requirements. Crew cost represents pilots and flight attendants for commercial flights. These costs do not include passenger costs nor operator costs due to capital recovery, management and other non-flight staffing, insurance, training, crew reserve, vacation and sick leave, non-flight maintenance contribution, and the like.

Table 9-7 FAA-Based 1996 Aircraft Operating Cost Rates

Engine		A/C	1996 Operating Cost Rate ($/minute)			Fuel & Oil		Delay-Applicable Total	
Type	No.	Size	Crew	Maint	Subtotal	Airborne	Ground	Departure	Arrival
J	4	H	41.47	28.32	69.78	45.05	15.02	84.80	114.83
J	4	L	9.70	16.50	26.20	13.82	4.61	30.81	40.02
J	3	H	33.02	24.32	57.33	30.45	10.15	67.48	87.78
J	3	L	19.80	11.87	31.67	17.08	5.69	37.36	48.75
J	3	S+	4.67	9.93	14.60	10.43	3.48	18.08	25.03
J	2	H	24.82	13.00	37.82	19.20	6.40	44.22	57.02
J	2	LH	19.40	8.22	27.62	12.57	4.19	31.81	40.18
J	2	L	14.18	8.85	23.03	10.85	3.62	26.65	33.88
J		L	na	na	na	na	na	23.76	30.35 [1]
J	2	LS	9.18	8.72	17.90	8.92	2.97	20.87	26.82
J	2	S+	4.18	8.58	12.77	7.00	2.33	15.10	19.77
J		S+	na	na	na	na	na	13.13	16.84 [1]
J	2	S	3.75	6.02	9.77	4.15	1.38	11.15	13.92
J	1	L	na	na	na	na	na	14.00	15.00 [1]
J	1	S+	na	na	na	na	na	10.00	11.00 [1]
J	1	S	na	na	na	na	na	6.00	7.00 [2]
T	4	L	11.20	16.63	27.83	9.52	3.17	31.01	37.35
T	3	L	na	na	na	na	na	20.83	25.50 [1]
T	2	L	3.42	5.73	9.15	4.50	1.50	10.65	13.65
T		L	na	na	na	na	na	10.03	12.53 [1]
T	2	S+	3.35	5.05	8.40	3.02	1.01	9.41	11.42
T		S+	na	na	na	na	na	8.86	10.68 [1]
T	2	S	3.22	4.28	7.50	2.45	0.82	8.32	9.95
T		S	na	na	na	na	na	6.60	8.03 [1]
T	1	S+	1.95	2.33	4.28	1.82	0.61	4.89	6.10
T	1	S	1.90	1.83	3.73	1.72	0.57	4.31	5.45
P	4	L	4.17	4.58	8.75	8.33	2.78	11.53	17.08
P	3	S	na	na	na	na	na	10.22	15.17 [1]
P	2	L	3.17	3.58	6.75	6.50	2.17	8.92	13.25
P	2	S+	3.33	3.40	6.73	3.22	1.07	7.81	9.95
P		S+	na	na	na	na	na	5.47	6.92 [1]
P	2	S	1.20	1.55	2.75	1.13	0.38	3.13	3.88
P		S	na	na	na	na	na	2.79	3.42 [1]
P	1	S+	1.20	1.00	2.20	0.75	0.25	2.45	2.95
P	1	S	1.20	0.45	1.65	0.37	0.12	1.77	2.02
J	8	H	na	na	na	na	na	84.80	114.83 [3]
SST (Rockwell B1B)			41.47	28.32	69.78	122.72	40.91	110.69	192.50

1. Interpolated
2. Extrapolated
3. Assumed same as J4H
na: not assigned

Table 9-8 1996/2015 Average Aircraft Operating Cost Rate by Study Site

	Average Aircraft Delay Operating Cost Rate* (1996 $/minute)			
	1996 Aircraft Mix		2015 Aircraft Mix	
Airport	Departures	Arrivals	Departures	Arrivals
DEN - Denver	$24.22	$30.95	$24.55	$31.21
DFW - Dallas-Ft. Worth	$20.32	$25.99	$23.30	$29.61
EWR - Newark	$23.52	$30.14	$25.33	$32.28
JFK - N.Y. Kennedy	$26.28	$34.29	$25.61	$32.97
LAX - Los Angeles	$23.01	$29.37	$23.69	$30.22
LGA - N.Y. LaGuardia	$22.25	$28.45	$23.06	$29.31
MSP - Minneapolis	$22.44	$28.67	$23.62	$30.02
ORD - Chicago O'Hare	$24.27	$31.14	$26.15	$33.33
PHL - Philadelphia	$21.00	$26.82	$22.47	$28.60
SFO - San Francisco	$26.50	$33.95	$27.54	$35.19

* Average value, weighted by aircraft class distribution.

Air Traffic System Modeling Process

The IAT Model is applied to the extended terminal airspace in which the DSTs operate. The model simulates each trajectory within the boundary of this area, assumed to be defined by an outer arc at the 250 nmi radius from the subject airport. These trajectories typically have an origin or destination outside the outer arc, which is the outer circle shown in Figure 9-1. The inner circle represents the boundary between the TRACON and en route airspace. Arrival metering fixes and departure fixes are on this inner boundary in the modeling.

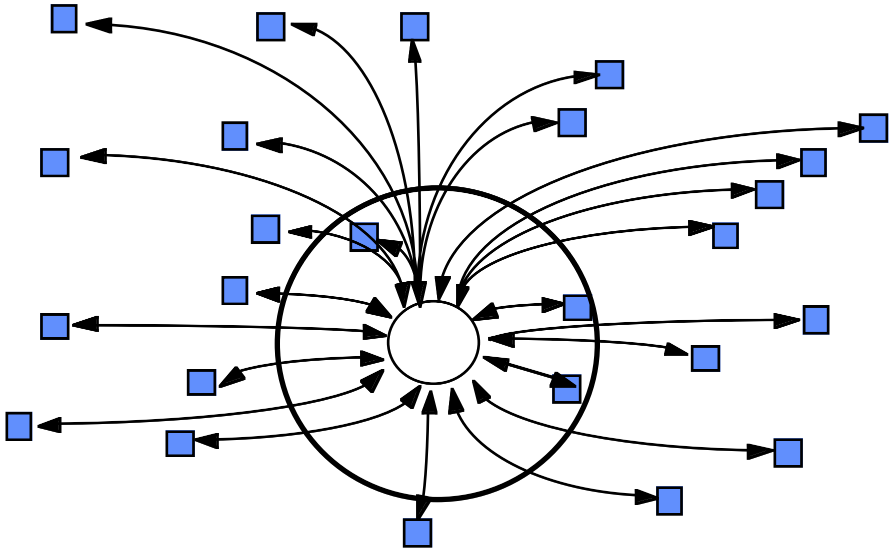


Figure 9-1 Extended Terminal Airspace (250 nmi radius) Modeling Scope

Key modeling factors used in determining delays and diversions from the planned trajectories and schedule for current and DST operations include:

- Trajectory variance with respect fix crossing time delivery accuracy
- Spacing buffer
- Delay distribution between TRACON and Center airspace
- Runway assignment
- Runway system operating procedures
- Airspace arrival and departure procedures

The procedures for modeling these factors are described in the following paragraphs.

Trajectory Accuracy and Aircraft Spacing

Previous studies [ref.15,17,18,22,36,37,38] have examined trajectory accuracies associated with new technologies and DSTs, and their impacts on air traffic operations. This research identified DSTs and also addressed supporting technologies such as data link communication, GPS navigation, and advanced flight management, surveillance, and meteorological systems. The impacts of these newly-developing advanced technologies on trajectory accuracy would be relevant to the potential benefits analysis future DST enhancements. The previous work defined and evaluated the trajectory error parameters pertaining to aircraft performance, maneuver actuation, atmospheric factors, and surveillance, and performed trajectory accuracy modeling to calibrate stochastic distributions describing trajectory variance (e.g., fix crossing time uncertainty) and spacing buffers associated with the DSTs. These analyses were augmented by data obtained from the prototype field tests at DFW [ref.15,16] with subsequent analysis.

The resulting trajectory variance and spacing buffer parameters at critical trajectory modeling points are listed in Table 9-9 and Appendix C; the appendix shows the runway threshold buffers. These parameters are the standard deviations of the trajectory variance and buffer distributions, and are defined separately for the current system and each DST. The trajectory variance parameter is used stochastically in the IAT Model to perturb travel times (to depict fix crossing delivery uncertainty), and the buffer parameter is used to emulate spacing planning. The IAT Model random perturbation process applies truncation, and is set to limit travel time stochastic variation to the one standard deviation value shown in Table 9-9.

Situations may occur in which deviations between actual and planned trajectories, acerbated by delay queuing with travel time perturbation, require controller intervention to resolve potential violations of minimum spacing requirements. In these cases, the planned trajectory would have been based on a spacing equal to the minimum separation requirement plus the buffer, but the shortest acceptable actual spacing is the minimum spacing requirement. The IAT modeling of the controller intervention stochastically defines a spacing based on a random selection from a uniform distribution bounded by the minimum separation requirement and by the minimum separation requirement plus the buffer.

Table 9-9 Trajectory Variance, Buffer and Spacing Parameters

	Current Sys	TMA	P-FAST	A-FAST	EDP	
Time Unit:	seconds					
	Trajectory Variance standard deviation					
En Route	180	90	180	180	90	sec
Terminal						
Arrival	28.34	28.34	26.06	24.94	24.94	sec
Departure	28.34	28.34	28.34	28.34	24.94	sec
Time Unit:	seconds					
	Excess Spacing Buffer					
Arr Fix	14.4	7.2	14.4	14.4	7.2	sec
Dep Fix	14.4	14.4	14.4	14.4	7.2	sec
R125	23.9	12.0	23.9	23.9	12.0	sec
R250	18.7	9.4	18.7	18.7	9.4	sec
	Minimum Separation Requirement					
Arr Fix	72.0	72.0	72.0	72.0	72.0	sec
Dep Fix	72.0	72.0	72.0	72.0	72.0	sec
R125	60.0	60.0	60.0	60.0	60.0	sec
R250	37.5	37.5	37.5	37.5	37.5	sec
	Spacing					
Arr Fix	86.4	79.2	86.4	86.4	79.2	sec
Dep Fix	86.4	86.4	86.4	86.4	84.0	sec
R125	83.9	72.0	83.9	83.9	72.0	sec
R250	56.2	46.9	56.2	56.2	46.9	sec
Distance Unit:	nmi					
	Excess Spacing Buffer					
Arr Fix	1.00	0.50	1.00	1.00	1.00	nmi
Dep Fix	1.00	1.00	1.00	1.00	0.50	nmi
R125	2.00	1.00	2.00	2.00	1.00	nmi
R250	2.50	1.25	2.50	2.50	1.25	nmi
	Minimum Separation Requirement					
Arr Fix	5.00	5.00	5.00	5.00	5.00	nmi
Dep Fix	5.00	5.00	5.00	5.00	5.00	nmi
R125	5.00	5.00	5.00	5.00	5.00	nmi
R250	5.00	5.00	5.00	5.00	5.00	nmi
Arr Fix	**Spacing**					
Dep Fix	6.00	5.50	6.00	6.00	5.50	nmi
R125	6.00	6.00	6.00	6.00	6.00	nmi
R250	7.00	6.00	7.00	7.00	6.00	nmi
	7.50	6.25	7.50	7.50	6.25	nmi

Notes: Speeds assumed to be 250 kts, 300 kts, and 480 kts at arr/dep fix, R125, and R250 respectively.
Buffer assumed to be a share of the sigma value. This share is assumed to be 0.080, 0.133, and 0.104 for arr/dep fix, R125, and R250 respectively.

Delay Distribution

An IAT Model logic module emulates the operation of the delay distribution function by simulating the delivery of arrival traffic to the metering fixes at rates designed to maintain a sufficient number of aircraft in the TRACON airspace to sustain optimum runway system acceptance, subject to TRACON airspace traffic loading constraints. The logic allows aircraft to absorb delay in Center airspace to achieve a balance between fuel economy and runway delay reduction. The delay distribution function logic is implemented in modelings of TMA and other DSTs as appropriate, but a modified version is applied to current system modeling to represent manual traffic management of inbound flows to a TRACON. This modeling process would be sensitive to the metering fix trajectory accuracy values defined for the current or DST system being modeled because the capability of the system to monitor correctly the flow into the TRACON depends on the magnitude of fix crossing time uncertainty. However, based on assessments by air traffic control local facility personnel obtained during a previous study of current operations [ref.15], a TRACON airspace delay absorption limit of 100 to 200 seconds per flight would be appropriate in the IAT Model applications. This limit would constrain the effectiveness of the DST delay distribution function relative to current operations. In this analysis, a TRACON airspace delay absorption limit of 100 seconds per flight is assumed at each of the 10 study sites. This conservative limit effectively eliminates TMA delay distribution fuel cost savings because flights would absorb the same amount of delay in the modeling of both current operations and TMA. However, reduced excess spacing gaps would be achieved with TMA, obtaining improved throughput and reducing delay relative to the current system.

Runway Assignment

The logical structure of the IAT Model runway assignment module is modified to represent the current or the DST system being simulated. The modeling of the current system is adapted for each airport according to known local operating procedures, and associates specific arrival and departure routes with a designated runway. Otherwise, runway assignment is based on geographic alignment between TRACON entry point and runway approach patterns. The runway assignment logic considers options to optimize runway system utilization to minimize delay. This logic is designed to assign arrival and departure flights to eligible runways according to least delay queue sizes. The logic emulates a process in which a minimum delay queue size parameter, which is defined separately for current and DST operations, is used to invoke runway reassignments. The modeling of the current and DST systems implementation of the runway assignment process is sensitive to the runway threshold trajectory accuracy and buffer values defined for each system.

Runway System Operations

The runway system module accounts for the aircraft separation procedures applicable to approach and departure operations through an airport's runway system and adjacent airspace. The model distinguishes VFR and IFR spacings required between two successive aircraft, including wake turbulence allowances. Matrixes of model input parameters for a specific airport runway use configuration describe pairwise spacings for the sequences of users of that runway system:

- arrival-arrival: a landing operation followed by another landing
- arrival-departure: a landing operation followed by a departure
- departure-arrival: a departure operation followed by an arrival
- departure-departure: a departure operation followed by another departure

A matrix of inter-aircraft minimum separation requirements [ref.33] by FAA aircraft weight class for a runway system being modeled is defined for each pairwise sequence, for both IFR and VFR procedures. These separation rule matrixes account for wake turbulence avoidance procedures as well as the runway occupancy characteristics for the subject airport. The FAA aircraft weight classes are heavy, large and small. These weight classes correspond to the aircraft size types listed in Table 9-2, except for the B757. The B757 is treated as a heavy aircraft for separation purposes in current practice, and is treated as such in the IAT Model. Otherwise, the large-to-heavy (LH), large (L), and large-to-small (LS) size types are modeled as large aircraft and small-to-large (S+) and small (S) size types are modeled as small aircraft for separation purposes. The spacing values in an IFR matrix are generally more stringent than the corresponding VFR spacings, subject to separation procedures.

A runway system may consist of a single runway, closely-spaced parallel runways, displaced parallel runways, crossing runways, converging or diverging runways, or combinations thereof. Operations on different runways are conducted independently or interdependently of each other based on spacing and geometric alignment of the runways and approach and departure procedures. One or a combination of these runway systems may represent an airport configuration. For example, Figure 9-2 shows the runway complex at Dallas-Ft. Worth International Airport for a south flow operation. The complex consists of two sets of dependent parallel runway pairs with a single third parallel runway, and a pair of parallel diagonal runways. In this operating configuration, each pair of parallel runways has one runway dedicated to arrivals and the other to departures. The single parallel and one of the diagonal runways are dedicated to arrivals while the remaining diagonal runway is dedicated to departures.

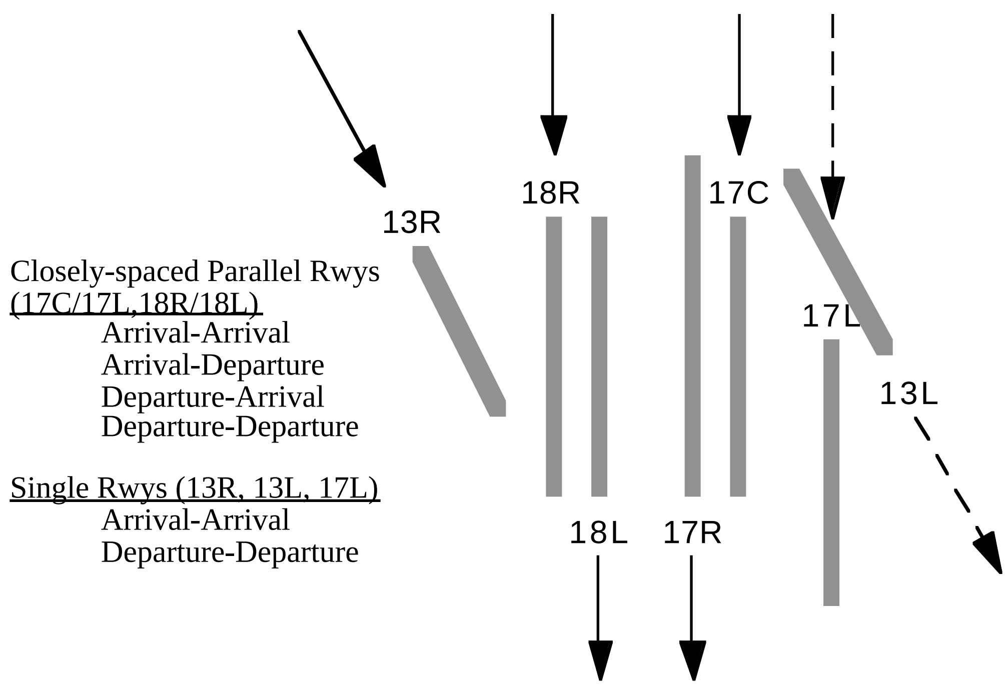


Figure 9-2 Runway Configuration, Dallas-Ft. Worth International Airport

Each entry in a matrix specifies the minimum spacing the model will allow between two successive aircraft using a runway system based on each aircraft's weight class and runway assignment for IFR or VFR operations. A single, unchanging set of minimum separation requirements matrixes for each airport is applied in all modelings of current and DST systems in this study.

An example of IFR minimum separation requirements is shown in Table 9-10. With reference to Figure 9-2, Table 9-10 tabulates the minimum separation required between two consecutive arrivals to runway 18R in the set of dependent parallel runways, 18R and 18L, by aircraft weight class pair. These minimum separations and are specified in units of both distance and time.

Table 9-10 Example Arrival-Arrival IFR Minimum Separation Requirement, Runway 18R, Dallas-Ft. Worth International Airport

	Minimum Separation Requirement							
	Trailing Aircraft							
Lead	Distance (nmi)				Time* (seconds)			
Aircraft	Small	Large	757	Heavy	Small	Large	757	Heavy
Small	2.5	2.5	2.5	2.5	75	72	72	66.67
Large	4	2.5	2.5	2.5	120	72	72	66.67
757	5	4	4	4	150	115.2	115.2	106.67
Heavy	6	5	5	4	180	144	144	106.67

* Time spacing based on trailing aircraft speeds: S is 120kts, L and 757 are 125kts, H is 135knts

Additional matrices would define other IFR minimum spacings for the dependent parallel runway operation such as a departure on 18L followed by an arrival on 18R or an arrival on 18R followed by a departure on 18L. Another matrix would define IFR minimum spacings for a departure pair on 18L. Other matrixes would define IFR operations on other runways such as 13R as well as VFR operations for all runways.

For this study, minimum time spacings are defined for IFR and VFR operations for the pairwise sequences appropriate for the runway systems defined for each of the 10 subject airports. A 2.5 nmi minimum separation procedure is assumed to apply at DFW and at certain other airports based on published descriptions [ref.39] and guidance provided by the FAA. [ref.40] The system of runways serving arrivals and departures corresponds to the runway use or operating configuration assumed at each airport. For this study, two runway configurations may be modeled at each airport representing an IFR configuration during IMC and a VFR configuration during VMC. The assumed runway configurations applied to each of the 10 airports are described in Appendix C.

Airspace Arrival And Departure Procedures

Data describing arrival and departure routes and associated altitude and speed restrictions for each or the 10 subject airports are encoded for input into the IAT Model to enable simulation of airspace operations at each site. These data are derived from published procedures [ref.41,42] and consultations with local authorities. Figure 9-3 and Table 9-11 present the arrival and departure routes and initial runway assignments modeled for DFW. The airspace procedures used to represent operations at the 10 airports are described in Appendix D. Using these data, a variable dual arrival fix process is assumed in the IAT modeling of DFW. The DFW arrival operation has a four corner “post” arrangement in which each post has a pair of arrival fixes (e.g., BAMBE, GREGS at the northwest post). The modeling emulates a plan in which only one post operates with both its arrival fixes simultaneously while the other three posts operate with one arrival fix. In our modeling, the dual arrival fix is assigned hourly to the post with the largest scheduled traffic volume during that hour.

In this application of the IAT Model, airspace arrival and departure trajectories are assumed to be procedurally separated at each of the 10 study sites. The planned arrival trajectories are modeled as being vertically or geographically separated from planned departure trajectories except for the runway system. Apart from runway system interactions, arrivals are treated independently of departures with respect to controller intervention requirements. This modeling approach focuses the analysis results on DST impacts rather than ATC airspace procedural impacts.

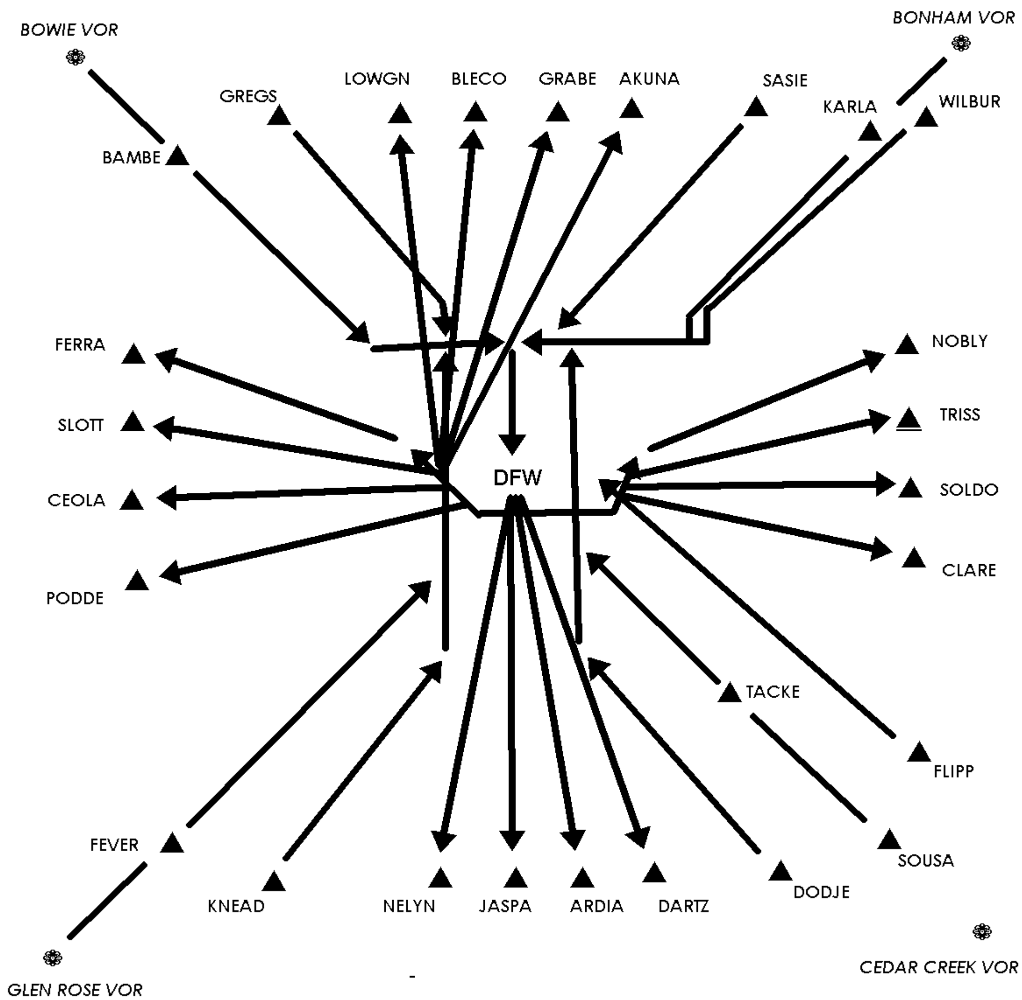


Figure 9-3 Arrival and Departure Routes, South Operation, Dallas-Ft. Worth International Airport

Table 9-11 Runway Assignment by Arrival and Departure Fix, South Operation, Dallas-Ft. Worth International Airport

Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
DFW	IFR	BAMBE	13R	NOBLY	13L
		GREGS	13R	TRISS	13L
				SOLDO	13L
				CLARE	13L
		SASIE	17C	FERRA	17R
		KARLA	17C	SLOTT	17R
				CEOLA	17R
				PODDE	17R
				NELYN	17R
				JASPA	17R
				ARDIA	17R
				DARTZ	17R
		FLIPP	18R	LOWGN	18L
		TACKE	18R	BLECO	18L
		DODJE	18R	GRABE	18L
		KNEAD	18R	AKUNA	18L
		FEVER	18R		
	VFR	BAMBE	13R	NOBLY	13L
		GREGS	13R	TRISS	13L
				SOLDO	13L
				CLARE	13L
		SASIE	17C	FERRA	17R
		KARLA	17C	SLOTT	17R
				CEOLA	17R
				PODDE	17R
				NELYN	17R
				JASPA	17R
				ARDIA	17R
				DARTZ	17R
		TACKE	17L	LOWGN	18L
				BLECO	18L
				GRABE	18L
				AKUNA	18L
		FLIPP	18R		
		DODJE	18R		
		KNEAD			
		FEVER			

Model Application

The IAT Model results describe the delay and diversion experienced by each simulated departure, arrival and overfight operation and the time of occurrence of each operation. The modeling results are processed to compile statistics describing the total number of operations and the total aircraft delay and operating costs during each hour of the sample day for arrival and departure operations. These data are used to calculate average aircraft delay and operating costs for each hour for both arrival and departure operations at each airport under study for each of the current system and DST modeling cases. The hourly traffic and delay data are illustrated in Appendix E for DFW. These modeling results are used to initiate the delay and cost analysis process leading to estimates of cost savings. The process calculates the average aircraft delays and operating costs categorized by IFR and VFR operations and sub-categorized by arrival and departure operations.

Each application of the IAT Model is adapted to evaluate either an IMC or a VMC day for the subject airport.

Aircraft Delay and Operating Costs

VFR average aircraft delay and operating cost savings are estimated by calculating the arithmetic mean delay and cost savings across aircraft classes during the 15-hour period between 7 AM and 10 PM local time of the VMC analysis. This period chosen because traffic activity during the other hours is typically very light, and the associated inconsequential delay may inaccurately distort the results.

For IFR delay analysis, the morning 5-hour period beginning at 7 AM is used based on an analysis of historic weather data [ref.43] for 11 airports, 8 of which are our study subjects. This analysis, summarized in Appendix F, shows that the duration of continuous IMC is likely to be five hours or less. Although IMC does not routinely persist for exactly five hours, this modeling approach facilitates representation of real-world complexities, thereby providing a data basis for analysis.

Delay severity is impacted by the duration of continuous IMC. Lesser delays are expected during shorter periods of IMC persistence than during longer ones. The analysis of weather observations at 11 airports [ref.43] shown in Appendix F is used to account for the relationship between IMC duration and delay. These observations describe Category I weather occurrences, which we use to represent IMC. Appendix F identifies the frequency of occurrence of continuous IMC by hourly duration. With reference to Appendix F, the historic duration of IMC persistence at eight of the subject airports, given that IMC exists, is summarized by the distribution shown in Table 9-12. At the remaining airports, where detailed hourly data were not available, an IMC duration distribution is used that represents an average of the 11 airports. This average is also included in Table 9-12.

Table 9-12 IMC Persistence by Airport

	Percent of IMC Time by Duration (hours) of Continuous IMC						
Airport	0 - 1 hrs	1 - 2 hrs	2 - 3 hrs	3 - 4 hrs	4 - 5 hrs	>5 hrs	Total
Atlanta (ATL)	25%	15%	11%	8%	7%	33%	100%
Boston (BOS)	28%	17%	9%	7%	4%	35%	100%
Dallas-Ft. Worth (DFW)	39%	16%	11%	6%	5%	23%	100%
Denver (DEN)	29%	18%	13%	8%	6%	27%	100%
Detroit (DTW)	32%	16%	12%	8%	6%	27%	100%
Newark (EWR)	29%	17%	10%	7%	5%	33%	100%
N.Y. Kennedy (JFK)	27%	16%	9%	6%	5%	36%	100%
Los Angeles (LAX)	23%	16%	13%	10%	8%	30%	100%
N.Y. LaGuardia (LGA)	24%	13%	9%	9%	6%	39%	100%
Chicago (ORD)	30%	14%	11%	9%	6%	30%	100%
San Francisco (SFO)	33%	19%	11%	8%	6%	22%	100%
Average*	29%	16%	11%	8%	6%	30%	100%

* Average value used for other airports.

The DFW weather data show that 39% of the total time spent in IMC consists of instrument conditions that persists for no more than one hour. Additionally, 77% of all DFW IMC periods persist for no more than five hours.

IFR average aircraft delay and operating cost are calculated using the modeling results obtained for each hour of the 5-hour IMC time span. For this analysis, the first hour of IFR delay begins at 7 AM local time, and the fifth hour of IFR duration ends at 12 Noon local time. First, the average delay (analogous to the VFR data illustrated for DFW in Appendix E), and cost saving for a specific hour(s) of IMC duration, illustrated for DFW in Appendix E, are multiplied by the corresponding IMC persistence percentage, given in Table 9-12. The persistence percentages by hour are normalized so their sum is 100% over the five hour IMC time span. Then, the IFR weighted average aircraft delay and cost respectively are determined by summing these products. The calculations are performed separately for arrivals and departures.

Results

The resulting estimated average delays and operating costs experienced by IFR and VFR departures and arrivals are tabulated for each airport for current system and each DST operation. The arrival data are tabulated at the runway and the departure data are tabulated at the departure fix. Comparisons of the delay and cost estimates show differences due to changes in airport-specific traffic volume, demand profile, airport runway capacity and procedures during IMC and VMC periods. The most severe delay and associated cost consequences would occur when IMC coincides with a heavy traffic surge.

These tabulations are used to derive average aircraft delay, delay saving and operating cost saving for each DST relative to current system operations as described in the following paragraphs. These data then are used to extrapolate annual savings at 43 airports.

Average Aircraft Delay

The average aircraft delay by IFR and VFR arrival and departure operation for each airport for 1996 and 2015 is tabulated in the Table 9-13 set for each DST for the Current System and the DSTs. These values represent the average aircraft delay across all aircraft classes. Average aircraft delay is shown to be greater for IFR than VFR operations at each airport in Table 1-13. This result is anticipated because VFR spacing procedures are less restrictive.

Table 9-13.1 Current System Average Aircraft Delay

	Average Aircraft Delay (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.06	2.22	1.02	2.40	2.74	4.09	2.64	4.07
DFW - Dallas-Ft. Worth	1.12	2.56	0.90	3.21	3.83	6.17	4.19	7.41
EWR - Newark	7.17	11.46	2.01	3.18	20.67	24.33	23.58	25.60
JFK - N.Y. Kennedy	0.70	1.43	4.21	6.36	1.12	2.79	7.15	10.14
LAX - Los Angeles	5.23	8.25	2.70	8.48	22.86	20.86	19.33	38.48
LGA - N.Y. LaGuardia	1.79	2.85	2.70	5.12	4.23	5.83	16.66	25.87
MSP - Minneapolis	21.54	27.21	12.98	13.19	44.16	47.83	77.96	53.59
ORD - Chicago O'Hare	12.57	18.99	21.75	18.43	25.80	35.78	78.85	51.83
PHL - Philadelphia	1.44	3.30	1.93	6.42	5.38	8.20	16.49	48.39
SFO - San Francisco	11.29	21.59	15.57	17.73	23.53	47.61	132.29	120.20
Average*	6.39	9.98	6.58	8.45	15.43	20.35	37.91	38.56

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-13.2 TMA/Multi-Center Average Aircraft Delay

	Average Aircraft Delay (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.03	1.46	0.98	1.65	2.65	3.32	2.60	3.24
DFW - Dallas-Ft. Worth	0.89	1.84	0.89	2.26	3.32	5.23	4.15	6.31
EWR - Newark	6.40	10.61	1.84	2.53	20.08	23.54	23.48	25.03
JFK - N.Y. Kennedy	0.69	0.97	4.10	5.82	1.07	2.29	6.96	9.48
LAX - Los Angeles	4.39	7.43	2.34	7.64	22.32	20.41	18.41	37.16
LGA - N.Y. LaGuardia	1.20	1.98	1.84	4.08	3.39	4.82	15.49	24.52
MSP - Minneapolis	21.72	27.02	12.61	12.55	44.09	47.78	77.48	53.18
ORD - Chicago O'Hare	11.66	18.06	21.46	17.68	25.70	35.59	78.58	51.17
PHL - Philadelphia	1.26	2.72	1.73	5.42	5.13	7.74	16.26	47.74
SFO - San Francisco	11.06	21.53	14.22	16.26	23.40	47.32	132.16	120.08
Average*	6.03	9.36	6.20	7.59	15.11	19.80	37.56	37.79

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-13.3 pFAST Average Aircraft Delay

	Average Aircraft Delay (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.06	2.08	1.01	2.35	2.62	3.97	2.66	3.93
DFW - Dallas-Ft. Worth	1.13	2.52	0.90	3.14	3.84	6.04	4.11	7.29
EWR - Newark	5.93	10.08	1.95	2.99	20.18	22.69	21.14	23.10
JFK - N.Y. Kennedy	0.75	1.36	4.00	5.76	1.12	2.77	6.79	9.24
LAX - Los Angeles	5.31	8.05	2.81	7.60	22.27	19.28	19.44	36.20
LGA - N.Y. LaGuardia	1.69	2.71	2.63	4.93	4.40	5.78	15.74	23.30
MSP - Minneapolis	20.99	26.55	12.40	12.60	42.33	46.30	75.71	53.14
ORD - Chicago O'Hare	12.62	18.69	19.30	16.82	25.45	34.29	78.31	48.78
PHL - Philadelphia	1.43	3.24	1.81	5.64	5.16	7.84	15.35	44.71
SFO - San Francisco	10.78	20.72	14.62	16.62	23.26	46.92	132.29	118.88
Average*	6.17	9.60	6.14	7.84	15.06	19.59	37.15	36.86

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-13.4 aFAST Average Aircraft Delay

	Average Aircraft Delay (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.06	2.08	1.00	2.31	2.61	3.92	2.63	3.89
DFW - Dallas-Ft. Worth	1.14	2.53	0.90	3.11	4.08	6.25	4.15	7.25
EWR - Newark	5.91	10.06	1.92	2.99	20.72	23.22	20.06	22.10
JFK - N.Y. Kennedy	0.74	1.34	3.93	5.48	1.11	2.76	6.58	8.96
LAX - Los Angeles	5.27	7.74	2.80	7.39	22.69	19.13	18.98	33.92
LGA - N.Y. LaGuardia	1.64	2.64	2.68	4.88	4.09	5.38	16.80	23.89
MSP - Minneapolis	20.29	25.95	12.03	12.28	41.32	45.37	74.64	52.15
ORD - Chicago O'Hare	12.52	18.44	18.31	16.03	25.75	34.30	78.18	47.39
PHL - Philadelphia	1.40	3.19	1.83	5.48	5.15	7.65	14.73	42.91
SFO - San Francisco	10.75	20.43	13.09	14.95	23.26	46.19	132.92	119.14
Average*	6.07	9.44	5.85	7.49	15.08	19.42	36.97	36.16

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-13.5 EDP Average Aircraft Delay

	Average Aircraft Delay (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.00	1.35	0.92	1.55	2.55	3.14	2.54	3.00
DFW - Dallas-Ft. Worth	0.86	1.77	0.84	2.20	3.50	5.15	4.00	5.96
EWR - Newark	4.81	8.89	1.73	2.33	20.21	22.72	19.86	21.33
JFK - N.Y. Kennedy	0.67	0.94	3.80	4.94	1.05	2.25	6.39	8.32
LAX - Los Angeles	4.49	6.99	2.36	6.48	21.94	18.62	17.66	32.13
LGA - N.Y. LaGuardia	1.09	1.84	1.87	3.88	3.21	4.40	15.67	22.71
MSP - Minneapolis	19.62	25.17	11.63	11.59	40.95	44.85	74.16	51.53
ORD - Chicago O'Hare	11.63	17.44	17.91	15.30	25.62	34.14	77.33	46.41
PHL - Philadelphia	1.15	2.56	1.57	4.64	4.87	7.07	14.48	42.05
SFO - San Francisco	10.54	20.20	11.69	13.48	22.80	45.58	132.79	119.03
Average*	5.59	8.72	5.43	6.64	14.67	18.79	36.49	35.25

* Simple arithmetic average, not weighted by airport traffic distributions

Average Aircraft Delay Saving

Delay saving due to a DST is calculated based on the arithmetic difference between the delays with Current System and the DST operation. The resulting average aircraft delay savings by IFR and

VFR arrival and departure operations for all aircraft classes are listed in the Table 9-14 set by airport for 1996 and 2015 by DST.

Table 9-14.1 TMA/Multi-Center Average Aircraft Delay Savings Relative to Current System

	Average Aircraft Delay Saving (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	0.03	0.76	0.05	0.74	0.08	0.77	0.04	0.83
DFW - Dallas-Ft. Worth	0.23	0.72	0.01	0.94	0.51	0.94	0.04	1.10
EWR - Newark	0.77	0.85	0.17	0.65	0.60	0.79	0.11	0.58
JFK - N.Y. Kennedy	0.01	0.46	0.11	0.54	0.05	0.50	0.19	0.65
LAX - Los Angeles	0.84	0.82	0.37	0.84	0.54	0.45	0.93	1.32
LGA - N.Y. LaGuardia	0.58	0.87	0.86	1.03	0.84	1.01	1.17	1.35
MSP - Minneapolis	0.00	0.19	0.37	0.64	0.07	0.05	0.48	0.40
ORD - Chicago O'Hare	0.91	0.93	0.29	0.75	0.11	0.19	0.28	0.66
PHL - Philadelphia	0.18	0.58	0.21	1.00	0.25	0.46	0.23	0.65
SFO - San Francisco	0.23	0.05	1.34	1.47	0.13	0.29	0.13	0.12
Average*	0.38	0.62	0.38	0.86	0.32	0.54	0.36	0.77

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-14.2 pFAST Average Aircraft Delay Savings Relative to Current System

	Average Aircraft Delay Saving (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	0.00	0.14	0.01	0.04	0.12	0.12	0.00	0.14
DFW - Dallas-Ft. Worth	0.00	0.03	0.00	0.06	0.00	0.13	0.08	0.12
EWR - Newark	1.24	1.39	0.06	0.19	0.49	1.64	2.44	2.51
JFK - N.Y. Kennedy	0.00	0.07	0.21	0.60	0.00	0.02	0.36	0.89
LAX - Los Angeles	0.00	0.20	0.00	0.88	0.60	1.58	0.00	2.28
LGA - N.Y. LaGuardia	0.10	0.14	0.07	0.18	0.00	0.05	0.92	2.57
MSP - Minneapolis	0.56	0.66	0.58	0.59	1.83	1.53	2.25	0.45
ORD - Chicago O'Hare	0.00	0.30	2.44	1.61	0.35	1.49	0.55	3.05
PHL - Philadelphia	0.01	0.06	0.12	0.78	0.22	0.36	1.14	3.68
SFO - San Francisco	0.51	0.87	0.95	1.11	0.28	0.68	0.00	1.32
Average*	0.24	0.38	0.44	0.61	0.39	0.76	0.77	1.70

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-14.3 aFAST Average Aircraft Delay Savings Relative to Current System

	Average Aircraft Delay Saving (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	0.00	0.15	0.02	0.09	0.12	0.17	0.01	0.18
DFW - Dallas-Ft. Worth	0.00	0.02	0.00	0.09	0.00	0.00	0.05	0.16
EWR - Newark	1.27	1.40	0.09	0.19	0.00	1.11	3.53	3.50
JFK - N.Y. Kennedy	0.00	0.09	0.29	0.88	0.01	0.03	0.56	1.18
LAX - Los Angeles	0.00	0.51	0.00	1.09	0.18	1.73	0.36	4.56
LGA - N.Y. LaGuardia	0.15	0.21	0.02	0.24	0.15	0.45	0.00	1.98
MSP - Minneapolis	1.25	1.26	0.95	0.90	2.84	2.46	3.32	1.44
ORD - Chicago O’Hare	0.04	0.55	3.43	2.40	0.05	1.48	0.68	4.45
PHL - Philadelphia	0.04	0.11	0.10	0.94	0.23	0.55	1.76	5.49
SFO - San Francisco	0.54	1.15	2.48	2.78	0.27	1.42	0.00	1.06
Average*	0.33	0.55	0.74	0.96	0.38	0.94	1.03	2.40

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-14.4 EDP Average Aircraft Delay Savings Relative to Current System

	Average Aircraft Delay Saving (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	1.00	0.87	0.10	0.85	2.55	0.95	0.09	1.07
DFW - Dallas-Ft. Worth	0.86	0.79	0.06	1.00	3.50	1.01	0.19	1.45
EWR - Newark	4.81	2.57	0.28	0.85	20.21	1.61	3.72	4.27
JFK - N.Y. Kennedy	0.67	0.48	0.42	1.42	1.05	0.54	0.76	1.82
LAX - Los Angeles	4.49	1.26	0.34	2.00	21.94	2.24	1.67	6.35
LGA - N.Y. LaGuardia	1.09	1.01	0.83	1.24	3.21	1.43	0.98	3.16
MSP - Minneapolis	19.62	2.03	1.35	1.60	40.95	2.97	3.81	2.06
ORD - Chicago O’Hare	11.63	1.55	3.84	3.13	25.62	1.65	1.53	5.43
PHL - Philadelphia	1.15	0.73	0.37	1.78	4.87	1.13	2.01	6.34
SFO - San Francisco	10.54	1.39	3.88	4.26	22.80	2.03	0.00	1.17
Average*	5.59	1.27	1.15	1.81	14.67	1.56	1.48	3.31

* Simple arithmetic average, not weighted by airport traffic distributions

Average Aircraft Delay Cost Saving

Delay cost saving due to a DST is calculated as the product of the delay saving due to this enhancement and the appropriate average aircraft direct operating cost rate. The average operating cost rates applicable to departure and arrival delays, previously presented in Table 9-8, are used to obtain the results shown in the Tables 9-15 set by airport for 1996 and 2015 for each DST.

Table 9-15.1 TMA/Multi-Center Average Aircraft Delay Cost Savings Relative to Current System

	Average Aircraft Operating Cost Saving (1996 $/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	$0.71	$23.55	$1.13	$22.99	$2.05	$24.07	$0.99	$26.03
DFW - Dallas-Ft. Worth	$4.63	$18.64	$0.12	$24.46	$11.87	$27.80	$1.01	$32.44
EWR - Newark	$18.16	$25.59	$4.04	$19.47	$15.14	$25.38	$2.71	$18.56
JFK - N.Y. Kennedy	$0.22	$15.63	$3.00	$18.44	$1.30	$16.51	$4.89	$21.56
LAX - Los Angeles	$19.28	$23.98	$8.41	$24.66	$12.91	$13.61	$21.96	$39.80
LGA - N.Y. LaGuardia	$12.93	$24.70	$19.09	$29.36	$19.42	$29.47	$26.99	$39.71
MSP - Minneapolis	$0.00	$5.42	$8.31	$18.25	$1.76	$1.60	$11.37	$12.07
ORD - Chicago O'Hare	$22.12	$28.99	$7.02	$23.35	$2.79	$6.25	$7.25	$22.09
PHL - Philadelphia	$3.87	$15.50	$4.35	$26.90	$5.63	$13.03	$5.08	$18.57
SFO - San Francisco	$6.16	$1.86	$35.59	$50.05	$3.49	$10.17	$3.51	$4.05
Average*	$8.81	$18.38	$9.11	$25.79	$7.64	$16.79	$8.58	$23.49

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-15.2 pFAST Average Aircraft Delay Cost Savings Relative to Current System

	Average Aircraft Operating Cost Saving (1996 $/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	$0.00	$4.26	$0.26	$1.38	$2.92	$3.66	$0.00	$4.30
DFW - Dallas-Ft. Worth	$0.00	$0.91	$0.00	$1.67	$0.00	$3.71	$1.87	$3.58
EWR - Newark	$29.26	$41.79	$1.35	$5.66	$12.38	$52.84	$61.87	$80.88
JFK - N.Y. Kennedy	$0.00	$2.44	$5.56	$20.69	$0.00	$0.65	$9.22	$29.49
LAX - Los Angeles	$0.00	$5.84	$0.00	$25.89	$14.11	$47.69	$0.00	$68.96
LGA - N.Y. LaGuardia	$2.19	$3.84	$1.56	$5.25	$0.00	$1.37	$21.27	$75.41
MSP - Minneapolis	$12.47	$18.80	$13.11	$16.90	$43.21	$45.88	$53.19	$13.38
ORD - Chicago O'Hare	$0.00	$9.43	$59.33	$50.24	$9.15	$49.59	$14.26	$101.62
PHL - Philadelphia	$0.28	$1.50	$2.60	$20.98	$4.85	$10.28	$25.61	$105.31
SFO - San Francisco	$13.60	$29.49	$25.05	$37.73	$7.59	$23.99	$0.00	$46.41
Average*	$5.78	$11.83	$10.88	$18.64	$9.42	$23.97	$18.73	$52.93

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-15.3 aFAST Average Aircraft Delay Cost Savings Relative to Current System

	Average Aircraft Operating Cost Saving (1996 $/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	$0.00	$4.54	$0.49	$2.79	$3.03	$5.23	$0.20	$5.72
DFW - Dallas-Ft. Worth	$0.00	$0.64	$0.01	$2.44	$0.00	$0.00	$1.06	$4.64
EWR - Newark	$29.77	$42.34	$2.12	$5.87	$0.00	$35.92	$89.31	$113.00
JFK - N.Y. Kennedy	$0.00	$3.07	$7.49	$30.20	$0.13	$0.91	$14.41	$38.98
LAX - Los Angeles	$0.00	$14.97	$0.00	$32.06	$4.15	$52.31	$8.42	$137.84
LGA - N.Y. LaGuardia	$3.25	$5.89	$0.38	$6.77	$3.36	$13.10	$0.00	$58.14
MSP - Minneapolis	$28.09	$36.02	$21.23	$25.94	$67.04	$73.90	$78.44	$43.09
ORD - Chicago O'Hare	$1.03	$17.16	$83.34	$74.60	$1.35	$49.25	$17.73	$148.17
PHL - Philadelphia	$0.94	$2.98	$2.11	$25.30	$5.13	$15.73	$39.52	$156.88
SFO - San Francisco	$14.23	$39.11	$65.77	$94.37	$7.48	$49.83	$0.00	$37.33
Average*	$7.73	$16.67	$18.29	$30.03	$9.17	$29.62	$24.91	$74.38

* Simple arithmetic average, not weighted by airport traffic distributions

Table 9-15.4 EDP Average Aircraft Delay Cost Savings Relative to Current System

	Average Aircraft Operating Cost Saving (1996 $/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	$24.12	$26.84	$2.53	$26.24	$62.71	$29.51	$2.33	$33.35
DFW - Dallas-Ft. Worth	$17.49	$20.55	$1.19	$26.08	$81.48	$30.04	$4.50	$42.82
EWR - Newark	$113.24	$77.50	$6.53	$25.67	$511.82	$52.08	$94.26	$137.90
JFK - N.Y. Kennedy	$17.56	$16.57	$10.93	$48.77	$26.79	$17.93	$19.44	$60.00
LAX - Los Angeles	$103.31	$37.01	$7.79	$58.63	$519.67	$67.71	$39.61	$191.77
LGA - N.Y. LaGuardia	$24.27	$28.59	$18.40	$35.16	$74.12	$41.79	$22.67	$92.61
MSP - Minneapolis	$440.31	$58.25	$30.38	$45.91	$967.15	$89.31	$89.91	$61.76
ORD - Chicago O'Hare	$282.31	$48.27	$93.14	$97.57	$669.87	$54.86	$39.89	$180.84
PHL - Philadelphia	$24.13	$19.70	$7.73	$47.72	$109.41	$32.18	$45.19	$181.32
SFO - San Francisco	$279.24	$47.15	$102.77	$144.55	$627.90	$71.28	$0.00	$41.22
Average*	$132.60	$38.04	$28.14	$55.63	$365.09	$48.67	$35.78	$102.36

* Simple arithmetic average, not weighted by airport traffic distributions

Annual Cost Savings Extrapolations

Factors relating to the estimation of annual delay cost savings are presented in Table 9-16 for 43 airports for 1996 and 2015. Two information items are shown in this table: the historical annual distribution of IMC and the forecast annual number of operations.

The annual percent of time each airport is under IMC is obtained from the ceiling-visibility study of historic climatological data. [ref.44] These data represent airport conditions when visibility is less than three miles and/or the ceiling is at or below 1500 feet.

The total annual number of takeoff and landing operations at each airport is obtained from FAA forecasts. [ref.32] The number of annual IMC operations is the product of the total operations and annual percent of IMC at each airport. The remainder is the number of annual VMC operations.

IMC-VMC Average Aircraft Delay Cost Saving

For the purpose of supporting annual cost savings extrapolations, the average aircraft delay cost savings estimates by arrivals and departures are consolidated into the IMC and VMC categories as follows. The annual forecasts assume an equal number of arrivals and departures at each airport. Similarly, we assume an equal distribution of arrivals and departures during IMC over an annual period; the same distribution is assumed for VMC arrivals and departures. The corresponding average aircraft delay cost savings are calculated by assigning a 50% weighting to both the arrival and departure cost saving previously shown in the Table 9-15 set. The resulting annual average aircraft cost savings for IFR and VFR operations are listed in the Table 9-17 set for the 10 study airport sites for 1996 and 2015. These tables also list the corresponding overall average cost saving, which is obtained by weighting the IFR and VFR values according to the distributions of annual IMC in Table 9-16.

Table 9-16 Annual Meteorological and Traffic Distribution by Airport

	Annual Occurrence of IMC 7am-10pm[1]	Number of Operations [2] (thousands)					
		1996			2015		
Airport	(percent)	Total	IMC	VMC	Total	IMC	VMC
Study Site							
DEN - Denver	6.0%	454	27	427	626	38	588
DFW - Dallas-Ft. Worth	8.4%	870	73	797	1500	126	1374
EWR - Newark	16.6%	443	74	370	643	107	536
JFK - N.Y. Kennedy	15.0%	361	54	306	425	64	361
LAX - Los Angeles	22.2%	764	170	594	1087	241	846
LGA - N.Y. LaGuardia	16.4%	343	56	286	408	67	341
MSP - Minneapolis	11.6%	484	56	427	722	84	638
ORD - Chicago O’Hare	16.1%	909	146	763	1147	185	962
PHL - Philadelphia	15.0%	406	61	345	583	87	495
SFO - San Francisco	12.5%	442	55	387	677	85	592

Table 9-16 Annual Meteorological and Traffic Distribution by Airport (concluded)

Airport	Annual Occurrence of IMC 7am-10pm[1] (percent)	Number of Operations[2] (thousands) 1996 Total	1996 IMC	1996 VMC	2015 Total	2015 IMC	2015 VMC
Non-Study Site							
ATL - Atlanta	14.2%	773	110	663	1025	145	879
BDL - Bradley	14.6%	161	23	137	215	31	184
BNA - Nashville	9.5%	226	21	205	288	27	260
BOS - Boston	15.6%	463	72	390	541	84	456
BWI - Baltimore-Washington	12.4%	270	33	237	405	50	355
CLE - Cleveland	15.6%	291	45	246	438	68	370
CLT - Charlotte	12.5%	457	57	400	643	80	563
COS - Colorado Springs	5.4%	227	12	215	314	17	297
CVG - Cincinnati	15.0%	394	59	334	775	116	658
DAB - Daytona Beach	6.0%	269	16	253	309	19	291
DCA - Washington National	10.7%	310	33	277	332	36	297
DTW - Detroit	16.6%	531	88	443	840	139	700
FLL - Ft. Lauderdale	3.0%	236	7	229	356	11	345
HOU - Houston Hobby	13.5%	252	34	218	313	42	271
HPN - Westchester Co.	19.5%	193	38	155	202	39	162
IAD - Washington Dulles	11.7%	330	39	292	457	53	403
IAH - Houston International	12.7%	392	50	342	694	88	606
LAS - Las Vegas	0.3%	480	1	478	812	2	810
LGB - Long Beach	19.7%	482	95	387	566	111	454
MCO - Orlando	5.9%	342	20	322	631	37	594
MDW - Chicago Midway	15.1%	254	38	216	331	50	281
MEM - Memphis	9.2%	364	33	330	558	51	506
MIA - Miami	2.3%	546	13	534	817	19	799
OAK - Oakland	14.4%	516	74	442	638	92	546
PDX - Portland	10.2%	306	31	275	468	48	420
PHX - Phoenix	0.5%	544	3	542	833	4	829
PIT - Pittsburgh	24.6%	447	110	337	617	152	465
SAN - San Diego	12.6%	244	31	213	367	46	321
SDF - Louisville	10.7%	173	19	155	248	27	221
SEA - Seattle	14.9%	398	59	338	581	87	494
SLC - Salt Lake City	5.6%	374	21	353	585	33	552
STL - St. Louis	11.5%	517	59	458	734	84	649
TEB - Teterboro	21.9%	193	42	151	193	42	151

1. Annual meteorological data source: Federal Aviation Administration, “Ceiling and Climatological Study and system Enhancement Factors,” Final Report FAA Office of Aviation System Plans, Washington, DC 20591 (June 1975).
2. Source for annual operations data: Federal Aviation Administration, "1997 Terminal Area Forecast (TAF) System," Office of Aviation Policy and Plans, Washington, DC 20591, Internet WWW Site (Oct 1998)

Table 9-17.1 TMA/Multi-Center IMC-VMC Annual Average Aircraft Delay Cost Savings Relative to Current System

	Annual Average [1] Aircraft Operating Cost Saving (1996 $/operation)					
	1996			2015		
Airport	IFR	VFR	All	IFR	VFR	All[2]
DEN - Denver	12.13	12.06	12.07	13.06	13.51	13.48
DFW - Dallas-Ft. Worth	11.63	12.29	12.23	19.83	16.73	16.99
EWR - Newark	21.88	11.76	13.44	20.26	10.63	12.23
JFK - N.Y. Kennedy	7.92	10.72	10.30	8.91	13.23	12.58
LAX - Los Angeles	21.63	16.53	17.66	13.26	30.88	26.97
LGA - N.Y. LaGuardia	18.81	24.22	23.34	24.45	33.35	31.89
MSP - Minneapolis	2.71	13.28	12.05	1.68	11.72	10.55
ORD - Chicago O'Hare	25.55	15.19	16.86	4.52	14.67	13.04
PHL - Philadelphia	9.69	15.62	14.73	9.33	11.82	11.45
SFO - San Francisco	4.01	42.82	37.97	6.83	3.78	4.16
Average[3]	13.60	17.45	17.06	12.21	16.03	15.33

1. Annual Average: 50% departures, 50% arrivals

2. All: weighted by IMC annual occurrence distribution

3. Average: simple arithmetic average, not weighted by airport traffic distributions

Table 9-17.2 pFAST IMC-VMC Annual Average Aircraft Delay Cost Savings Relative to Current System

	Annual Average [1] Aircraft Operating Cost Saving (1996 $/operation)					
	1996			2015		
Airport	IFR	VFR	All	IFR	VFR	All[2]
DEN - Denver	2.13	0.82	0.90	3.29	2.15	2.22
DFW - Dallas-Ft. Worth	0.45	0.83	0.80	1.85	2.72	2.65
EWR - Newark	35.53	3.51	8.82	32.61	71.38	64.94
JFK - N.Y. Kennedy	1.22	13.12	11.34	0.33	19.35	16.50
LAX - Los Angeles	2.92	12.94	10.72	30.90	34.48	33.68
LGA - N.Y. LaGuardia	3.02	3.41	3.34	0.68	48.34	40.53
MSP - Minneapolis	15.63	15.00	15.08	44.55	33.28	34.59
ORD - Chicago O'Hare	4.72	54.78	46.72	29.37	57.94	53.34
PHL - Philadelphia	0.89	11.79	10.15	7.56	65.46	56.78
SFO - San Francisco	21.55	31.39	30.16	15.79	23.20	22.28
Average[3]	8.80	14.76	13.80	16.69	35.83	32.75

1. Annual Average: 50% departures, 50% arrivals

2. All: weighted by IMC annual occurrence distribution

3. Average: simple arithmetic average, not weighted by airport traffic distributions

Table 9-17.3 aFAST IMC-VMC Annual Average Aircraft Delay Cost Savings Relative to Current System

	Annual Average [1] Aircraft Operating Cost Saving (1996 $/operation)					
	1996			2015		
Airport	IFR	VFR	All	IFR	VFR	All[2]
DEN - Denver	2.27	1.64	1.68	4.13	2.96	3.03
DFW - Dallas-Ft. Worth	0.32	1.22	1.15	0.00	2.85	2.61
EWR - Newark	36.05	4.00	9.32	17.96	101.16	87.35
JFK - N.Y. Kennedy	1.53	18.85	16.25	0.52	26.70	22.77
LAX - Los Angeles	7.49	16.03	14.13	28.23	73.13	63.16
LGA - N.Y. LaGuardia	4.57	3.57	3.74	8.23	29.07	25.65
MSP - Minneapolis	32.05	23.59	24.57	70.47	60.77	61.89
ORD - Chicago O'Hare	9.10	78.97	67.72	25.30	82.95	73.67
PHL - Philadelphia	1.96	13.71	11.94	10.43	98.20	85.04
SFO - San Francisco	26.67	80.07	73.39	28.66	18.67	19.92
Average[3]	12.20	24.16	22.39	19.39	49.64	44.51

1. Annual Average: 50% departures, 50% arrivals
2. All: weighted by IMC annual occurrence distribution
3. Average: simple arithmetic average, not weighted by airport traffic distributions

Table 9-17.4 EDP IMC-VMC Annual Average Aircraft Delay Cost Savings Relative to Current System

	Annual Average [1] Aircraft Operating Cost Saving (1996 $/operation)					
	1996			2015		
Airport	IFR	VFR	All	IFR	VFR	All[2]
DEN - Denver	25.48	14.38	15.05	46.11	17.84	19.54
DFW - Dallas-Ft. Worth	19.02	13.64	14.09	55.76	23.66	26.36
EWR - Newark	95.37	16.10	29.26	281.95	116.08	143.61
JFK - N.Y. Kennedy	17.06	29.85	27.93	22.36	39.72	37.11
LAX - Los Angeles	70.16	33.21	41.42	293.69	115.69	155.21
LGA - N.Y. LaGuardia	26.43	26.78	26.72	57.96	57.64	57.69
MSP - Minneapolis	249.28	38.15	62.64	528.23	75.83	128.31
ORD - Chicago O'Hare	165.29	95.36	106.62	362.36	110.37	150.94
PHL - Philadelphia	21.92	27.73	26.85	70.79	113.26	106.89
SFO - San Francisco	163.20	123.66	128.60	349.59	20.61	61.73
Average[3]	85.32	41.89	47.92	206.88	69.07	88.74

1. Annual Average: 50% departures, 50% arrivals
2. All: weighted by IMC annual occurrence distribution
3. Average: simple arithmetic average, not weighted by airport traffic distributions

Study Sites Annual Cost Savings

The extrapolated potential annual aircraft operating cost savings at the 10 study sites due to each DST relative to current operations is calculated by summing the product of the annual number of operations during IMC or VMC (Table 9-16) at each airport and the corresponding IMC or VMC average aircraft cost savings (Table 9-17). The resulting potential annual cost savings due to each DST are presented in the Table 9-18 set.

Table 9-18.1 TMA/Multi-Center Annual Delay Cost Savings Relative to Current System for Study Sites

	Annual Operating Cost Savings (1996$ million)					
	1996			2015		
Airport	IFR	VFR	Total	IFR	VFR	Total
DEN - Denver	0.33	5.15	5.48	0.49	7.95	8.44
DFW - Dallas-Ft. Worth	0.85	9.79	10.64	2.50	22.98	25.48
EWR - Newark	1.61	4.34	5.95	2.16	5.70	7.87
JFK - N.Y. Kennedy	0.43	3.29	3.72	0.57	4.78	5.35
LAX - Los Angeles	3.67	9.83	13.50	3.20	26.11	29.31
LGA - N.Y. LaGuardia	1.06	6.95	8.00	1.64	11.38	13.01
MSP - Minneapolis	0.15	5.68	5.83	0.14	7.48	7.62
ORD - Chicago O'Hare	3.74	11.58	15.32	0.83	14.12	14.95
PHL - Philadelphia	0.59	5.39	5.98	0.82	5.86	6.68
SFO - San Francisco	0.22	16.56	16.78	0.58	2.24	2.82
Total	12.65	78.56	91.21	12.93	108.60	121.52

Table 9-18.2 pFAST Annual Delay Cost Savings Relative to Current System for Study Sites

	Annual Operating Cost Savings (1996$ million)					
	1996			2015		
Airport	IFR	VFR	Total	IFR	VFR	Total
DEN - Denver	0.06	0.35	0.41	0.12	1.27	1.39
DFW - Dallas-Ft. Worth	0.03	0.66	0.70	0.23	3.74	3.97
EWR - Newark	2.61	1.30	3.91	3.48	38.28	41.76
JFK - N.Y. Kennedy	0.07	4.03	4.09	0.02	6.99	7.01
LAX - Los Angeles	0.49	7.69	8.19	7.46	29.16	36.61
LGA - N.Y. LaGuardia	0.17	0.98	1.15	0.05	16.49	16.54
MSP - Minneapolis	0.88	6.42	7.30	3.73	21.24	24.97
ORD - Chicago O'Hare	0.69	41.78	42.47	5.42	55.75	61.18
PHL - Philadelphia	0.05	4.07	4.12	0.66	32.44	33.10
SFO - San Francisco	1.19	12.14	13.33	1.34	13.75	15.08
Total	6.25	79.42	85.66	22.51	219.10	241.62

Table 9-18.3 aFAST Annual Delay Cost Savings Relative to Current System for Study Sites

	Annual Operating Cost Savings (1996$ million)					
	1996			2015		
Airport	IFR	VFR	Total	IFR	VFR	Total
DEN - Denver	0.06	0.70	0.76	0.16	1.74	1.90
DFW - Dallas-Ft. Worth	0.02	0.97	1.00	0.00	3.92	3.92
EWR - Newark	2.65	1.48	4.13	1.92	54.25	56.16
JFK - N.Y. Kennedy	0.08	5.78	5.87	0.03	9.64	9.68
LAX - Los Angeles	1.27	9.53	10.80	6.81	61.84	68.65
LGA - N.Y. LaGuardia	0.26	1.03	1.28	0.55	9.92	10.47
MSP - Minneapolis	1.80	10.09	11.89	5.90	38.79	44.69
ORD - Chicago O'Hare	1.33	60.22	61.55	4.67	79.83	84.50
PHL - Philadelphia	0.12	4.73	4.85	0.91	48.66	49.58
SFO - San Francisco	1.47	30.97	32.44	2.43	11.06	13.48
Total	9.07	125.50	134.57	23.38	319.64	343.02

Table 9-18.4 EDP Annual Delay Cost Savings Relative to Current System for Study Sites

	Annual Operating Cost Savings (1996$ million)					
	1996			2015		
Airport	IFR	VFR	Total	IFR	VFR	Total
DEN - Denver	0.69	6.14	6.83	1.73	10.50	12.23
DFW - Dallas-Ft. Worth	1.39	10.87	12.26	7.03	32.51	39.53
EWR - Newark	7.01	5.95	12.96	30.09	62.25	92.34
JFK - N.Y. Kennedy	0.92	9.16	10.08	1.43	14.35	15.77
LAX - Los Angeles	11.90	19.74	31.64	70.87	97.84	168.71
LGA - N.Y. LaGuardia	1.49	7.68	9.17	3.88	19.66	23.54
MSP - Minneapolis	14.00	16.32	30.32	44.24	48.40	92.64
ORD - Chicago O'Hare	24.19	72.73	96.91	66.92	106.21	173.13
PHL - Philadelphia	1.33	9.57	10.90	6.19	56.12	62.32
SFO - San Francisco	9.02	47.83	56.84	29.58	12.21	41.79
Total	71.94	205.97	277.92	261.96	460.04	722.00

Table 9-19 summarizes the total annual aircraft operating cost savings estimated for each DST by study site for 1996 and 2015. The total savings generally conform with expectations based on DST functionality and traffic growth. For example, aFAST functionally enhances pFAST operations and estimated savings due to aFAST generally are greater than those due to pFAST in each year. Similarly, EDP functionality synergistically encompasses TMA, pFAST and aFAST by integrating arrivals and departures into its operation; and estimated savings due to EDP generally are greater than those of the other DSTs. Traffic loadings in 2015 are significantly heavier than in 1996, which would acerbate delay. The resulting opportunity to alleviate these increased delays by DSTs is demonstrated by their generally significantly greater estimated savings in 2015 than in 1996.

Table 9-19 TMA, pFAST, aFAST and EDP Potential Annual Cost Savings Relative to the Current System

	Annual Aircraft Delay Cost Savings (1996 $ millions)							
	1996				2015			
Airport	TMA	pFAST	aFAST	EDP	TMA	pFAST	aFAST	EDP
DEN - Denver	5.48	0.41	0.76	6.83	8.44	1.39	1.90	12.23
DFW - Dallas-Ft. Worth	10.64	0.70	1.00	12.26	25.48	3.97	3.92	39.53
EWR - Newark [1]	5.95	3.91	4.13	12.96	7.87	41.76	56.16	92.34
JFK - N.Y. Kennedy [1]	3.72	4.09	5.87	10.08	5.35	7.01	9.68	15.77
LAX - Los Angeles	13.50	8.19	10.80	31.64	29.31	36.61	68.65	168.71
LGA - N.Y. LaGuardia [1]	8.00	1.15	1.28	9.17	13.01	16.54	10.47	23.54
MSP - Minneapolis	5.83	7.30	11.89	30.32	7.62	24.97	44.69	92.64
ORD - Chicago O'Hare	15.32	42.47	61.55	96.91	14.95	61.18	84.50	173.13
PHL - Philadelphia [1]	5.98	4.12	4.85	10.90	6.68	33.10	49.58	62.32
SFO - San Francisco	16.78	13.33	32.44	56.84	2.82	15.08	13.48	41.79
Total	91.21	85.66	134.57	277.92	121.52	241.62	343.02	722.00

1. Multi-Center TMA

However, Table 9-19 shows some anomalies with respect total annual aircraft operating cost saving estimates that differ from expectations. The results for SFO show less estimated savings in 2015 than in 1996 for TMA, aFAST and EDP. Also, the estimated savings are less for aFAST than pFAST for SFO and LGA in 2015. A much less significant but similar difference is shown for DFW. These anomalies may be due to the traffic data and modeling process applied. The 2015 traffic loadings are hypothetically extrapolations of 1996 traffic, and the specific traffic peaking characteristics generated for 2015 would determine the delay and aircraft operating cost savings results produced by the airspace and runway system modelings. Also, the stochastic effects emulated in the modelings could introduce aberrant results, although the thousands of flights simulated would dampen distortions due to randomness. We note the IAT Model is newly-developed and further examination of its operation is appropriate to verify its air traffic analysis applicability.

Non-study Sites Annual Cost Savings

Table 9-20 presents average aircraft operating cost by arrival and departure for 1996 and 2015 for the 33 non-study sites. The operating costs at the 33 non-study sites are based on the distribution [ref.32] of annual operations by user classes at each site as described in Appendix G.

Published delay data [ref.45] by airport are used to guide the extrapolation of annual delay cost savings for the 33 non-study sites. These published delay data are derived from various reports of delay statistics and operations counts. These delay statistics are a combination of airport ground delay and origin-to-destination flight delay reports and estimates, and are not directly comparable to the extended terminal airspace-specific, DST-sensitive aircraft delays estimated in this study. However, the published statistics enable a ranking of the relative severity of delay for the non-study sites so that specific non-study sites may by associated with a correspondingly ranked study site. This correlation identifies the study site whose delay savings characteristic are to be used as a surrogate for that of its similarly-ranked non-study sites.

This representation procedure does not use data from the study sites, SFO and LGA, with significantly anomalous delay results (see the above discussion accompanying Table 9-19). The procedure also does not use data from that study site, ORD, which has the generally greatest overall estimated savings magnitude (see Table 9-19). The potential savings determined for these three sites are excluded to avoid distorting the non-study site benefits estimates or biasing these estimates in favor of the DSTs. Hence, seven study sites are used to estimate aircraft operating cost savings due to DSTs at the non-study sites as summarized in the following.

The non-study site ranking process identifies the delay-ordered one-seventh percentile group in which each airport resides. The published delay statistics and rankings for the non-study sites are tabulated in Appendix G. This appendix also describes the study site rankings, which are based on the total annual aircraft operating cost savings estimates presented previously in Table 9-19. These surrogate airports are ranked for both 1996 and 2015 in Appendix G according their average savings across DSTs as a means to scale their relative impacts on potential benefits. The resulting ranking and surrogate airport assignments are summarized in Table 21. A rank value of 1 identifies the group containing one-seventh (14.3%) of the non-study site airports with the most delay; a ranking equal to 2 identifies the group containing 14.3% of these airports with the second most delay; and so forth.

The average aircraft delay savings in minutes per operation previously determined (Table 14) for each of the surrogate airports are applied to the correspondingly-ranked non-study site as assigned in Table 21. For example, the Table 14 delay savings for Los Angeles (LAX) are used to represent the Atlanta (ATL), St. Louis (STL), Cincinnati (CVG), Boston (BOS) and Detroit (DTW) sites for 1996 as well as 2015. Total annual delay saving during IMC and VMC by non-study site is calculated as the product of the:

- annual number of arrivals or departures during IMC or VMC (i.e., 50% of the appropriate entry in Table 9-16), and
- the average delay savings per arrival or departure (minutes per operation) during IMC or VMC (i.e., the appropriate surrogate airport entry in Table 14)

Total annual delay saving (minutes per airport) by arrival and departure category is the sum of the above-defined products obtained for each category's IMC and VMC components. Total annual cost saving by airport is calculated by applying that average aircraft operating cost by arrival or departure listed in Table 9-20 for each non-study site.

The resulting extrapolated potential annual aircraft operating cost savings for arrivals and departures at the 33 non-study sites due to each DST relative to current operations are presented in the Table 9-22 set. The corresponding estimated annual total cost savings are summarized in Table 9-23 for 1996 and 2015.

Table 9-20 Average Aircraft Operating Cost by Non-Study Site

Airport	Average Aircraft Operating Cost[1] (1996 $/min) 1996 Departure	1996 Arrival	2015 Departure	2015 Arrival
ATL - Atlanta	29.54	37.75	30.53	39.03
BDL - Bradley	16.92	21.72	18.70	23.91
BNA - Nashville	18.01	23.03	20.87	26.66
BOS - Boston	21.66	27.52	22.28	28.31
BWI - Baltimore-Washington	23.11	29.48	25.61	32.68
CLE - Cleveland	21.54	27.44	21.39	27.19
CLT - Charlotte	23.89	30.51	24.39	31.10
COS - Colorado Springs	13.14	17.47	15.34	20.12
CVG - Cincinnati	21.09	26.76	21.32	27.03
DAB - Daytona Beach	3.40	4.58	3.27	4.41
DCA - Washington National	23.30	29.81	23.57	30.13
DTW - Detroit	25.76	32.95	27.92	35.71
FLL - Ft. Lauderdale	18.14	23.17	23.13	29.59
HOU - Houston Hobby	18.64	23.94	20.41	26.16
HPN - Westchester Co.	5.21	6.74	7.09	9.07
IAD - Washington Dulles	14.88	18.88	16.25	20.58
IAH - Houston International	28.74	36.74	29.14	37.22
LAS - Las Vegas	23.26	29.92	27.62	35.44
LGB - Long Beach	2.88	3.91	3.39	4.56
MCO - Orlando	23.70	30.25	26.88	34.33
MDW - Chicago Midway	20.31	26.02	22.94	29.37
MEM - Memphis	22.14	28.31	23.93	30.57
MIA - Miami	23.65	30.21	26.56	33.93
OAK - Oakland	14.14	18.18	18.46	23.70
PDX - Portland	18.40	23.50	20.61	26.26
PHX - Phoenix	25.48	32.64	28.36	36.31
PIT - Pittsburgh	24.11	30.79	22.40	28.53
SAN - San Diego	25.76	32.96	27.50	35.16
SDF - Louisville	23.46	30.09	25.68	32.89
SEA - Seattle	24.78	31.54	27.01	34.44
SLC - Salt Lake City	21.65	27.69	24.30	31.05
STL - St. Louis	27.43	35.08	28.61	36.57
TEB - Teterboro	2.97	3.92	2.97	3.92

1. Average Aircraft Operating Cost data are weighted according user class traffic distribution for each airport.

Table 9-21 Airport Surrogate Assignments

Group Rank	Non-Study Site [1]	Surrogate Study Site 1996 [2]	Surrogate Study Site 2015 [2]
1	ATL	LAX	LAX
	STL		
	CVG		
	BOS		
	DTW		
2	CLT	MSP	EWR
	SLC		
	MIA		
	PIT		
	IAH		
3	CLE	EWR	MSP
	DCA		
	MEM		
	SEA		
	PHX		
4	FLL	PHL	PHL
	MCO		
	LAS		
	HOU		
	SDF		
5	PDX	DFW	DFW
	IAD		
	BDL		
	OAK		
	BWI		
6	BNA	JFK	JFK
	COS		
	SAN		
	MDW		
7	DAB	DEN	DEN
	HPN		
	LGB		
	TEB		

1. Rank based on: Federal Aviation Administration, “Consolidated Operations and Delay Analysis System (CODAS),” Office of Aviation Policy and Plans, Washington, DC 20591, FAA APO Home Page, Internet WWW Site (Oct 1998).

2. Rank based on total annual delay savings derived form Tables 9-19

Table 9-22.1 1996 Delay Cost Savings Relative to Current System for Non-Study Sites

	Aircraft Delay Cost Savings (1996 $ millions)							
	TMA/M-C TMA		pFAST		aFAST		EDP	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
ATL - Atlanta	4.94	12.20	0.00	11.44	0.00	14.72	10.59	27.59
BDL - Bradley	0.05	1.59	0.00	0.10	0.00	0.15	0.24	1.70
BNA - Nashville	0.21	1.38	0.39	1.44	0.53	2.10	0.90	3.47
BOS - Boston	2.20	5.32	0.00	4.93	0.00	6.37	4.94	11.97
BWI - Baltimore-Wash	0.10	3.64	0.00	0.24	0.00	0.34	0.49	3.89
CLE - Cleveland	0.83	2.71	0.76	1.50	0.86	1.53	3.09	4.47
CLT - Charlotte	1.77	4.05	3.17	4.17	5.37	6.61	19.86	11.54
COS - Colorado Springs	0.16	1.06	0.30	1.14	0.40	1.66	0.64	2.72
CVG - Cincinnati	1.81	4.40	0.00	4.10	0.00	5.29	3.99	9.93
DAB - Daytona Beach	0.02	0.46	0.00	0.03	0.01	0.06	0.07	0.52
DCA - Washington Natnl	0.85	3.08	0.67	1.46	0.78	1.50	2.75	4.78
DTW - Detroit	3.04	7.31	0.00	6.72	0.00	8.71	7.03	16.40
FLL - Ft. Lauderdale	0.44	2.71	0.26	2.08	0.21	2.51	0.84	4.79
HOU - Houston Hobby	0.48	2.86	0.26	2.07	0.22	2.51	1.11	4.95
HPN - Westchester Co.	0.02	0.48	0.00	0.04	0.01	0.07	0.14	0.55
IAD - Washington Dulles	0.08	2.85	0.00	0.19	0.00	0.27	0.38	3.05
IAH - Houston Intnl	1.82	4.17	3.27	4.30	5.55	6.83	20.69	11.92
LAS - Las Vegas	1.15	7.19	0.69	5.60	0.56	6.75	2.07	12.74
LGB - Long Beach	0.03	0.70	0.01	0.06	0.01	0.10	0.19	0.80
MCO - Orlando	0.83	5.06	0.47	3.82	0.39	4.62	1.68	8.88
MDW - Chicago Midway	0.25	1.74	0.46	1.73	0.63	2.52	1.17	4.24
MEM - Memphis	0.92	3.42	0.67	1.54	0.80	1.58	2.80	5.20
MIA - Miami	2.34	5.17	3.77	4.88	6.16	7.53	11.47	13.30
OAK - Oakland	0.14	4.27	0.00	0.28	0.00	0.39	0.64	4.57
PDX - Portland	0.08	3.30	0.00	0.22	0.00	0.31	0.40	3.53
PHX - Phoenix	1.21	5.75	0.44	1.72	0.67	1.78	2.08	7.64
PIT - Pittsburgh	1.51	3.63	3.11	4.17	5.51	6.83	31.54	11.76
SAN - San Diego	0.32	2.12	0.58	2.15	0.78	3.14	1.40	5.24
SDF - Louisville	0.42	2.49	0.23	1.84	0.19	2.23	0.92	4.34
SEA - Seattle	1.29	4.24	1.15	2.30	1.31	2.35	4.70	6.95
SLC - Salt Lake City	1.42	3.16	2.36	3.07	3.90	4.78	9.62	8.41
STL - St. Louis	2.98	7.59	0.00	7.29	0.00	9.30	5.79	17.35
TEB - Teterboro	0.01	0.28	0.00	0.02	0.00	0.04	0.09	0.32

Table 9-22.2 2015 Delay Cost Savings Relative to Current System for Non-Study Sites

Aircraft Delay Cost Savings (1996 $ millions)

Airport	TMA/M-C TMA Depart	TMA/M-C TMA Arrival	pFAST Depart	pFAST Arrival	aFAST Depart	aFAST Arrival	EDP Depart	EDP Arrival
ATL - Atlanta	13.65	23.87	1.32	43.62	5.16	83.16	71.15	115.22
BDL - Bradley	0.22	2.76	0.14	0.31	0.08	0.34	1.36	3.56
BNA - Nashville	0.53	2.45	0.98	3.11	1.53	4.11	2.36	6.51
BOS - Boston	5.22	9.04	0.56	16.62	1.97	31.52	29.10	43.65
BWI - Baltimore-Wash	0.52	7.12	0.36	0.80	0.21	0.91	3.13	9.22
CLE - Cleveland	1.96	2.07	10.24	3.66	15.20	9.50	44.96	13.10
CLT - Charlotte	1.32	6.01	17.24	23.97	24.19	32.02	45.33	39.39
COS - Colorado Springs	0.44	2.04	0.82	2.67	1.28	3.53	1.86	5.52
CVG - Cincinnati	7.18	12.43	0.74	22.78	2.71	43.31	38.90	59.99
DAB - Daytona Beach	0.02	0.57	0.00	0.09	0.01	0.12	0.12	0.72
DCA - Washington Natnl	1.71	1.82	8.64	2.81	12.80	7.73	30.46	10.78
DTW - Detroit	10.12	17.59	1.16	32.47	3.82	61.36	59.05	84.94
FLL - Ft. Lauderdale	0.93	3.39	4.58	18.86	7.05	28.10	8.63	32.55
HOU - Houston Hobby	0.73	2.55	3.24	13.23	4.95	19.72	7.65	23.06
HPN - Westchester Co.	0.03	0.75	0.02	0.12	0.02	0.16	0.41	0.96
IAD - Washington Dulles	0.36	5.06	0.26	0.57	0.15	0.65	2.15	6.56
IAH - Houston Intnl	1.71	7.78	22.19	30.94	31.13	41.31	58.80	50.82
LAS - Las Vegas	2.53	9.33	12.75	52.84	19.67	78.72	22.65	91.00
LGB - Long Beach	0.60	0.06	0.09	0.03	0.13	0.04	0.92	0.75
MCO - Orlando	3.73	2.46	2.88	11.76	4.41	18.08	9.56	23.62
MDW - Chicago Midway	1.62	0.83	0.06	1.49	0.09	2.33	2.14	3.90
MEM - Memphis	0.80	3.78	10.02	18.86	15.69	27.93	20.98	61.57
MIA - Miami	8.34	1.64	17.50	33.25	12.11	47.77	22.01	56.86
OAK - Oakland	0.65	8.11	0.40	0.92	0.23	1.01	3.94	10.46
PDX - Portland	0.44	6.64	0.35	0.75	0.20	0.87	2.56	8.62
PHX - Phoenix	5.66	6.05	26.59	6.83	39.22	21.79	47.18	31.19
PIT - Pittsburgh	1.57	5.52	13.56	20.17	18.37	25.64	53.73	31.84
SAN - San Diego	0.88	4.10	1.59	5.07	2.49	6.70	4.02	10.72
SDF - Louisville	0.73	2.56	3.31	13.57	5.08	20.22	7.38	23.58
SEA - Seattle	3.30	3.50	17.18	6.07	25.50	15.89	73.29	21.95
SLC - Salt Lake City	0.95	5.33	16.57	22.30	23.64	30.56	32.98	37.42
STL - St. Louis	9.27	16.33	0.72	29.53	3.51	56.84	42.01	78.82
TEB - Teterboro	0.01	0.31	0.01	0.05	0.01	0.07	0.18	0.39

Table 9-23 Total Annual Delay Cost Savings Relative to Current System for Non-Study Sites

Aircraft Delay Cost Savings (1996 $ millions)	
1996	2015

Airport	TMA	pFAST	aFAST	EDP	TMA	pFAST	aFAST	EDP
ATL - Atlanta	17.13	11.44	14.72	38.18	37.52	44.95	88.32	186.37
BDL - Bradley	1.64	0.10	0.15	1.94	2.98	0.45	0.42	4.92
BNA - Nashville	1.59	1.83	2.63	4.37	2.98	4.09	5.64	8.87
BOS - Boston	7.52	4.93	6.37	16.91	14.26	17.18	33.49	72.75
BWI - Baltimore-Wash	3.74	0.24	0.34	4.38	7.65	1.17	1.12	12.35
CLE - Cleveland	3.54	2.26	2.39	7.56	4.03	13.90	24.70	58.06
CLT - Charlotte	5.82	7.34	11.99	31.40	7.33	41.21	56.21	84.72
COS - Colorado Springs	1.22	1.44	2.07	3.36	2.48	3.49	4.81	7.39
CVG - Cincinnati	6.21	4.10	5.29	13.92	19.60	23.52	46.02	98.89
DAB - Daytona Beach	0.48	0.04	0.07	0.59	0.59	0.10	0.13	0.85
DCA - Washington Natnl	3.93	2.12	2.28	7.54	3.54	11.45	20.53	41.24
DTW - Detroit	10.35	6.72	8.71	23.43	27.72	33.63	65.17	144.00
FLL - Ft. Lauderdale	3.15	2.34	2.73	5.63	4.32	23.44	35.15	41.18
HOU - Houston Hobby	3.33	2.32	2.73	6.06	3.28	16.47	24.67	30.71
HPN - Westchester Co.	0.51	0.05	0.07	0.69	0.79	0.14	0.19	1.37
IAD - Washington Dulles	2.93	0.19	0.27	3.43	5.43	0.83	0.80	8.71
IAH - Houston Intnl	5.99	7.57	12.38	32.62	9.49	53.13	72.43	109.62
LAS - Las Vegas	8.34	6.28	7.31	14.81	11.87	65.59	98.39	113.65
LGB - Long Beach	0.73	0.07	0.11	1.00	0.66	0.12	0.17	1.66
MCO - Orlando	5.89	4.30	5.02	10.56	6.20	14.64	22.50	33.18
MDW - Chicago Midway	1.99	2.19	3.15	5.41	2.45	1.55	2.42	6.04
MEM - Memphis	4.34	2.21	2.38	8.00	4.58	28.89	43.62	82.55
MIA - Miami	7.51	8.65	13.70	24.77	9.98	50.74	59.88	78.86
OAK - Oakland	4.40	0.28	0.39	5.20	8.76	1.32	1.24	14.39
PDX - Portland	3.38	0.22	0.31	3.93	7.07	1.09	1.06	11.17
PHX - Phoenix	6.96	2.16	2.45	9.73	11.72	33.41	61.01	78.37
PIT - Pittsburgh	5.13	7.29	12.34	43.30	7.09	33.73	44.01	85.57
SAN - San Diego	2.43	2.73	3.92	6.64	4.98	6.66	9.19	14.74
SDF - Louisville	2.91	2.06	2.42	5.26	3.29	16.88	25.29	30.96
SEA - Seattle	5.53	3.45	3.66	11.64	6.80	23.25	41.39	95.24
SLC - Salt Lake City	4.58	5.43	8.68	18.03	6.28	38.87	54.19	70.40
STL - St. Louis	10.57	7.29	9.30	23.14	25.60	30.25	60.35	120.83
TEB - Teterboro	0.29	0.03	0.04	0.41	0.32	0.06	0.08	0.58

10. Engineering Analysis of Collaborative Arrival Planning and Other Impacts

Engineering analysis was used to quantitatively evaluate the potential benefits for the three types of CAP functionalities: CTAS-to-Airline Data Exchange, Airline-to-CTAS Data Exchange, and Intra-Airline Slot Swapping. The remainder of this section describes the quantitative engineering analysis results which were obtained during this study.

Note: In the generation of the CAP benefit impacts, the preliminary nature of the CAP technology and time and budget constraints precluded a detailed analysis of archived relevant airline operational data. Therefore, a heavy reliance on the expert judgment of American Airline operational personnel familiar with current airline operations and near-term CAP capabilities was made. Because of this, the results herein should be seen as a rough, first-cut estimation of CAP-related benefits that should be followed-up by more detailed studies of operational data and simulations to further examine the benefit potential of CAP and validate the current results. Also, as farther-term CAP technology begins to take shape, the assumed benefit mechanisms and benefit results will need to be adjusted as appropriate.

Also, where values of operational inefficiencies and costs were estimated, American Airlines made conservative estimates to avoid overpredicting future benefits accrued.

CTAS-to-Airline Data Exchange

A one-way CAP CTAS repeater, which transmits CTAS data to AOCs, provides dispatchers with timely updates of arrival time and delay predictions. Specifically, the airline operational use of updated prediction data results in reduced ground personnel and equipment, reduced baggage mishandling costs, reduced misconnections, and reduced arrival airport diversions. These are quantified hereafter through engineering analysis. These quantifications generally relied upon expert estimation of the frequency and magnitude of existing costs and potential benefits. This approach was taken due to the complexity, lack of time available to analyze existing operational airline databases, and the dearth of existing detailed airline operational modeling tools designed to evaluate the impact of improved arrival time predictions on airline decision-making. AAL operational data collected since the installation of the CAP CTAS repeater in 1998 was not deemed valid for analysis due to the experimental nature of the repeater's use.

In addition, for the purposes of this quantification, the current CAP CTAS repeater technology (e.g., one based on a TMA Build 2 repeater) and its associated arrival time predictions was assumed. Future CTAS technology improvements, with CAP airline-to-CTAS data exchange as one way to realize improvements, will increase arrival time predictions beyond that of the current CAP CTAS repeater.

<u>Reduced Ground Personnel and Equipment Costs</u> -- Reduced ground personnel and equipment costs due to CTAS-provided arrival predictions were estimated by American Airlines based on discussions with airport operations managers. Currently, American Airlines procedures require that one set of ground personnel and equipment exist at every gate, ready to initiate gate turnarounds, and, because of arrival uncertainty, it is sometimes difficult to allow ground personnel to take a lunch break, resulting in a frequent paying of overtime pay rates to compensate for missed lunches. Because of these current conditions and the fact that CTAS provides more accurate terminal area delay estimates, American Airlines ramp personnel believe that a one-way CTAS repeater can reduce ground personnel and equipment costs. Making a conservative estimate that ground personnel and equipment cannot be reduced, but the overtime costs can be eliminated, American Airlines calculated that $0.25 millions/year for DFW operations could be saved.

Because of the dependence of this benefit mechanism on the level of connectivity of an airline schedule and supporting gate network, CAP CTAS repeater benefits are only expected at major US hub airports. It is hard to find any rigid definition of a “hub” airport - except by the existence of an air carrier’s connected schedule. Since the set of such airports will change as a function of airline marketing strategies and schedules and the level of connectivity of air carrier schedules at airports is not tracked closely by air traffic databases (although it tends to correlate with a high total number of carrier operations at a given airport), the CAP benefits analysis relied on an American Airlines definition of the current US air carrier hub airports (shown in Table 10-1).

Table 10-1 Current Major US Air Carrier Hub Airports

US Air Carrier	Hub Airport	# of 1993 OAG Flights [1,ref.46]	Est. # of 1996 OAG Flights[2]
AAL	DFW	229,491	237,474
AAL	ORD	175,636	192,675
AAL	MIA	88,913	90,360
AWE	PHX	68,044	82,200
AWE	LAS	26,689	35,780
COA	IAH	118,288	144,200
COA	EWR	104,919	113,757
COA	CLE	54,287	66,174
DAL	ATL	249,367	311,877
DAL	DFW	127,876	132,324
DAL	CVG	122,764	150,939
DAL	SLC	78,868	90,721
FDX [3]	MEM	18,575	20,791
NWA	MSP	143,941	167,801
NWA	DTW	142,953	168,046
NWA	MEM	74,154	83,002
TWA	STL	136,740	177,306
TWA	JFK	46,998	50,842
UAL	ORD	185,216	203,184
UAL	DEN	125,749	115,049
UAL	SFO	109,897	123,251
UAL	IAD	74,902	77,183
USA	CLT	163,971	181,199
USA	PIT	163,673	161,220
USA	PHL	107,539	106,378
TOTAL		2,939,450	3,283,733

[1]These data are suspected to include all airline codeshare flights. For instance, flights attributed to American Airlines may include American Eagle flights. Further study is required to separate any commuter flights from the air carrier flights.

[2]Extrapolated from 1993 AAL data (in Column 3) by a fixed % growth based on 1993 and 1996 actual TAF air carrier flights per airport (in Columns 2 and 3 of Appendix W).

[3]A significant number of Federal Express’ unscheduled cargo flights will not show up in the OAG.

CAP benefits that would be available at these hubs should extend beyond just air carrier flights to commuter flights such as those from American Eagle. Additionally, benefits might also extend to other airports that have some level of flight connectivity (e.g., AAL operations at JFK), and, in the future, if current airline trends towards code-sharing results in more tightly integrated connections, CAP technology could provide additional benefits for these flights.

Making the assumption that the AAL-wide overtime benefits are proportional to their number of annual AAL arrivals at the 3 major hub airports - DFW, ORD, and MIA (although some benefits may extend to other airports with some level of schedule connectivity), one can estimate a rough-order-of-magnitude level of AAL-wide overtime benefits by multiplying the $0.25M/year (in 1998 dollars) at DFW savings by the ratio of annual AAL flights at the 3 hub airports to the number of annual AAL DFW flights. This ratio was estimated by dividing the sum of AAL 1993 scheduled flights at the 3 hub airports by the number of AAL 1993 scheduled flights at DFW which were obtained from a database merge of NASA-provided OAG North American and Worldwide data [ref.46]. This adjustment assumes that this ratio of scheduled flights has stayed constant since 1993 and it is not impacted by any discrepancy between scheduled and actual flights. Also, the assumption is made that DFW savings are representative for both ORD and MIA. Differences will exist, based on the actual schedules flown. For example, in the case of MIA, this assumption will result in an overestimate because, unlike DFW, MIA does not typically have a bank scheduled during lunch time.

Calculating the 3 hub-to-DFW ratio from the 1993 schedule data shown in Appendix W, one obtains the ratio value of 2.15. Multiplying this ratio by the $0.25M/year provides a rough-order-of-magnitude estimate of $0.5M/year (in 1996 $) saved by AAL in overtime costs at 3 hub airports (ignoring the impact of 1996-to-1998 inflation as a second order effect).

In addition, if, as some AAL dispatchers believe, the current AAL ground personnel and equipment procedures can be changed and the CTAS repeater can be used to obtain improved ground crew utilization rates, just a 1% reduction in ground crew costs would provide an additional $2M/year in savings [ref.47], just at DFW, - a figure that has the potential of roughly increasing the benefits over the AAL conservative overtime cost savings estimate by a factor of eight!

<u>Reduced Baggage Mishandling Costs</u>-- Quantitative evaluation of the potential baggage mishandling costs avoidable due to a CAP CTAS Repeater was investigated as follows. First of all, annual baggage mishandling costs due to insufficient time to connect the bags were determined by American Airlines to be $620,000/year at DFW.

Costs avoidable by the use of a CAP repeater will depend on the improved accuracy of CAP arrival time predictions over that of current airline predictions at roughly one hour before arrival - when the critical gate allocation decisions are being made. Also, the costs avoidable will also depend on airline ramp tower managers using this CAP information to make improved gate allocation decisions. Currently, the CAP repeater accuracy at this critical point for baggage movement decisions is unknown, but if the baggage mishandling costs can be reduced by 10%, this would result in a savings on the order of $62,000/year. Because of the requirement of a highly-connected schedule for this benefit mechanism, CAP benefits will only be expected at hub airports. A rough extrapolation to all of AAL operations at the 3 major hub airports are similar to that previously done in the case of the reduced ground personnel and equipment costs and would increase this figure by a factor of 2.15 to roughly $130,000/year. However, as in the previous case, this preliminary extrapolation makes assumptions that ignore some benefits at the non major-hub airports (e.g., JFK), potentially important correlating factors including the number of gates, gates per airport, and frequency of arrivals at an airport, and other assumptions involving the use of 1993 scheduled AAL operations data.

<u>Reduced Misconnection Costs</u> -- The quantitative estimation of this potential benefit mechanism was discussed by American Airlines operations coordinators, operations analysts, and ramp tower managers. Unfortunately, the outcome of these discussions was a consensus that a rough-order-of-magnitude estimate of current misconnection costs was infeasible given the time and budget constraints of this effort. First of all, this benefit mechanism is a very complex issue that has been historically quite difficult to address (especially at a high-level). Some of the issues that tend to make such analysis difficult include: the reasons for passenger misconnections can often be out of the airline's control (e.g., some passengers intentionally misconnect in order to game airline fare structures and other passengers unintentionally misconnect by staying too long at airport

restaurants, shopping, etc.). AAL has developed various passenger-tracking systems before, but because of a lack of internal consensus on the proper interpretation of the system output, the airline has not felt comfortable using them.

Potential misconnection cost reductions due to a CTAS repeater will depend on the frequency and magnitude of passenger misconnections, the delay incurred at the final destination, and the quantitative impact of increased arrival time prediction accuracy on better airline “hold-go” decisions that reduce the misconnections. AAL personnel felt that it is likely that misconnections under bad weather conditions would be severe enough that increased arrival time accuracy from a CAP repeater would be unlikely to provide any significant beneficial effect, and that under good weather conditions the misconnection rate is so low that this benefit mechanism is probably not very large. Conditions that would be conducive to potential benefits through the use of a CAP repeater would be misconnections that involve the last flight of the day or a misconnect to a low-frequency-flight international destination.

Due to the current lack of archived statistical data and the impact of real-time airline operations details on such benefits analysis, a detailed investigation of misconnection cost savings is recommended through the use of real-time airline operation playback simulations. Unfortunately, the budget involved in this effort did not allow for such a study. However, such a future study could involve the use of AAL’s T-DECS system (the Training version of the AAL Dispatcher Environmental Control System (DECS)) for a recent scenario of misconnections coupled with phone surveys of misconnected passengers.

<u>Reduced Low-Fuel Diversions</u> -- The potential for CTAS-to-Airline data exchange to reduce arrival airport diversions was estimated by American Airlines according to the following method. First, American Airlines used their archived DECS data to determine the number of annual low-fuel diversions that they typically experienced. 1997 operational data were used in order to avoid the recent impact of AAL use of the operational CTAS repeater (in operation since April 1998). The quantity of experienced low-fuel diversions will be a function of a number of factors including annual weather and air carrier fuel policy. The total number of low-fuel diversions experienced by American Airlines for 1997 was 82 and this data is broken down by destination airport in Table 10-2.

56 of the 1997 AAL low-fuel diversions occurred at the 43 target airports and 35 of the diversions occurred at AAL’s 3 major hubs. If roughly half of all the AAL low-fuel diversions which occurred at the 43 target airports could be avoided by dispatcher use of the CAP CTAS repeater, then the number of low-fuel diversions avoided would be 28 diversions per year.

Next, American Airlines determined the diversion costs (in 1997 dollars) for the low-fuel diversions which occurred at DFW, ORD, and MIA. This diversion cost calculation involved the estimation of delay costs per minute, by taking into account the magnitude of the delay and a delay multiplier, based on the time of day (for details on how a delay multiplier is calculated, see previous work done by American Airlines with Oakridge National Labs [ref.48]). These diversion delay costs will typically include the direct operating costs of the additional flight time to the alternate and back, costs required during its hold on the ground, any required passenger costs such as overnight hotel stays and food, any downstream schedule disruption-related costs for diversions from hubs, and any future passenger costs from diversion-caused ill will towards the airline. These diversion costs will also be a function of a number of variables including aircraft equipment type, time of day, frequency of downstream flight connections, and the degree of connectivity of the airline schedule. American Airlines calculated annual diversion costs of $300,000/year for the low-fuel diversions at DFW, ORD, and MIA. Taking into account that this cost was borne by 35 diversions, this results in an average diversions cost of roughly $9,000 per diversion.

Multiplying the rough-order-of-magnitude number of 28 annual avoidable AAL diversions by the average diversion costs of $9,000 per diversion provides a rough-order-of-magnitude annual savings of $300,000/year for AAL operations.

Table 10-2 1997 Low-Fuel Diversions by Destination Airport

Destination Airport	# of Low-Fuel Diversions in 1997
ALB	1
BDA	1
BDL	1
BNA	1
BOS	2
BUF	3
BUR	1
BWI	1
CLE	2
DFW	18
DTW	1
EGE	2
EWR	2
JFK	1
LAX	2
LGA	4
MIA	10
ONT	1
ORD	7
ORF	2
PHL	3
RDU	1
ROC	2
SEA	1
SJC	1
SWF	1
International Destinations	10
TOTAL	82

AAL CTAS Repeater Benefits Extrapolation -- A summary of the quantitative benefits estimated for AAL's use of the CTAS Repeater is shown in Table 10-3.

Assuming that CTAS repeater information would be desired and used by dispatchers responsible for all air carrier flights to the 43 target airports (which are assumed to have CTAS operational), the American Airlines avoided costs were extrapolated to potential avoided costs for all air carrier operations at the 43 target airports.

Table 10-3 Preliminary 1996 Rough-Order-of-Magnitude Estimated CTAS Repeater Benefits for AAL Operations

Benefit Mechanism	1996$ AAL Benefits ($millions/year)
Reduced Ground Personnel and Equipment	0.5
Reduced Baggage Mishandling Costs	0.1
Reduced Misconnections	Unknown, >0
Reduced Low-Fuel Diversions	0.3
TOTAL	>0.9

For benefit mechanisms such as the reduced ground personnel and equipment, reduced baggage mishandling costs, and reduced misconnections, which rely on a highly-connected flight schedule, the total nationwide benefits can be estimated by an extrapolation of results shown in Table 10-1 to all major US air carrier hub airports. This hub-related benefits extrapolation was performed by multiplying the AAL cost savings due to reduced ground personnel and equipment and reduced baggage mishandling costs by the ratio of the estimated 1996 air carrier operations at the major US hub airports (which were all in the group of 43 target airports) to the total estimated 1996 AAL operations at the hub airports. This extrapolation assumes that the avoidable costs at the US hub airports are statistically correlated to AAL's avoidable costs by a factor that is linear with the number of hub airport operations. Also, the extrapolation assumes, for all hub operations data, a constant ratio of air carrier flights to all OAG-mentioned flights (shown in Table 10-1). Taking the data from Table 10-1, the hub operations ratio was determined by dividing the total estimated 1996 hub operations from Table 10-1, equal to 3,283,733, by the total estimated 1996 AAL hub operations, equal to 520,509. The calculated operations ratio is equal to 6.31. Multiplying the 6.31 ratio by the each of the previously estimated AAL operational cost savings, results in a 1996 nationwide savings shown in Table 10-4.

In the case of the reduced low-fuel diversions, these benefits will not be as strong a function of the level of schedule connectivity, so the diversion savings was calculated as a function of the total number of air carrier operations at the target airports. This extrapolation was performed by multiplying the $300,000/year aggregate AAL cost savings by the ratio of the total air carrier operations at the 43 airports to the total American Airline operations at the 43 airports. This extrapolation assumes that the avoidable costs at the 43 target airports are statistically correlated to AAL's avoidable costs by a factor that is linear with the number of operations.

This ratio of air carrier arrivals at the 43 target airports to AAL air carrier arrivals was calculated by the following process. First, the annual 1996 air carrier arrivals at each of the 43 target airports was taken from the FAA's Terminal Area Forecasts [ref.32] and can be found in Appendix W. This total of annual air carrier arrivals at the 43 target airports was 4,897,838 arrivals for 1996. Then, this number was divided by the total AAL arrivals for the 43 target airports. These total AAL arrivals were determined by summing the total number of OAG scheduled flights for each of the 43 target airports taken from a merge of the 1993 OAG North American and 1993 OAG Worldwide files. [ref.46] These total 1993 AAL arrivals for the 43 target airports was 918,532. These AAL OAG arrivals were then corrected to air carrier arrivals, using a factor of 0.78 based on AAL DFW operations data. The total 1993 AAL air carrier arrivals for the 43 target airports was determined to be 716,455. These 1993 AAL air carrier arrivals were then scaled up to 1996 levels based on fixed percentage increases per airport from 1993 operations to 1996 operations that are observed in the FAA Terminal Area Forecasts (see Appendix W). This resulted in a total of 799,502 1996 estimated AAL arrivals. The final ratio of air carrier arrivals at the 43 target airports to the AAL air carrier arrivals is 6.13. Using the derived ratio and multiplying it by the AAL avoidable diversion costs results in 1996 potential benefit savings shown in Table 10-4.

Table 10-4 Preliminary 1996 CTAS Repeater Benefits Estimate for Nationwide Air Carrier Arrivals at the 43 Target Airports

Benefit Mechanism	1996 Benefits for Target Airports
	($millions/year)
Reduced Ground Personnel and Equipment	3.2
Reduced Baggage Mishandling Costs	0.8
Reduced Misconnections	Unknown, >0
Reduced Low-Fuel Diversions	1.8
TOTAL	>5.8

In order to derive the 2015 potential benefit savings, the estimated 1996 potential benefit savings from Table 10-4 were multiplied by the ratio of 2015 annual air carrier arrivals to the 1996 annual air carrier arrivals for the 43 target airports. Derived by taking the total annual 2015 arrivals at the 43 target airports, equal to 7,649,946 and dividing it by the total annual 1996 arrivals at the airports, equal to 4,897,838, from Appendix W, this ratio was equal to 1.56. The 2015 benefits estimates are shown in Table 10-5.

Table 10-5 Preliminary 2015 CTAS Repeater Benefits Estimate for Nationwide Air Carrier Arrivals at the 43 Target Airports

Benefit Mechanism	2015 Benefits for Target Airports
	($millions/year)
Reduced Ground Personnel and Equipment	5.0
Reduced Baggage Mishandling Costs	1.2
Reduced Misconnections	Unknown, >0
Reduced Low-Fuel Diversions	2.8
TOTAL	>9.0

Future CTAS Repeater Technology Benefits -- As CTAS Repeater technology increases through the incorporation of future NASA functionality such as EDA and User-CTAS data exchanges, CTAS arrival prediction accuracy will improve beyond its current level and additional CTAS Repeater benefits are expected.

Airline-to-CTAS Data Exchange

In addition to the CTAS repeater, the CAP program will enable future data exchanges of relevant AOC data (such as aircraft weight estimates, airborne wind/temp data, and satellite airport departure time data) to CTAS to improve CTAS trajectory prediction accuracies. These improvements in CTAS trajectory prediction accuracy, when achieved and used by air traffic controllers to provide improved clearances, have the potential to increase throughput, provide more fuel-efficient trajectories, and increase conflict detection accuracy which will result in reduced ATM trajectory interruptions. In this effort, quantification of these data exchange benefits focused on the potential throughput-related benefits of the data exchange of aircraft weight estimates and airborne wind/temp data.

Future efforts should quantitatively examine some of the other potential benefit categories and data exchanges.

For this study, we examined the impact of AOC-provided weight data exchange and forecasted improvements in wind/temp forecast accuracies due to airline-provided airborne wind/temp data. These data are assumed to improve controller arrival metering fix delivery accuracy with associated potential airport throughput improvements and direct operating cost savings.

Seagull used its Trajectory Accuracy and Traffic Spacing Model, outlined in Figure 10-1, to calculate the impact of the weight and airborne wind/temp data on the threshold excess spacing buffer. This is the same method used to calculate the threshold buffers used in the IAT model of the other DSTs.

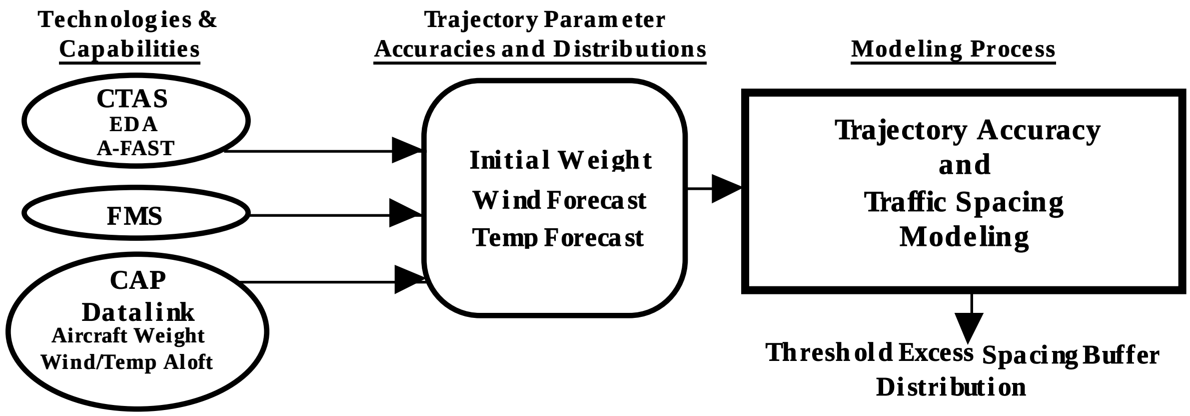


Figure 10-1: Threshold Excess Spacing Buffer Calculation Process

Using the assumptions of improved CAP data-exchanged variances in aircraft weight and wind/temp forecasts with a baseline of EDA and A-FAST, the Trajectory Accuracy and Traffic Spacing Model was used to determine the appropriate threshold spacing buffers using trajectory simulations of aircraft trajectories from cruise to final approach. A baseline of EDA and A-FAST is used because these improvements to CTAS trajectory prediction may not be captured in the data provided to controllers by TMA and P-FAST. Capturing the full benefit of CAP data exchange improvements are likely to require CTAS-calculated maneuver advisories, available with EDA and A-FAST.

Current and CAP-enhanced weight and wind/temp accuracies were determined from previous CTAS data exchange benefit studies. [ref.49] A summary of the assumed nominal and CAP data exchange-enhanced standard deviation errors of weight and wind speed and temperature forecasts is shown in Table 10-6.

Table 10-6 Assumed Nominal and CAP Data Exchange-Enhanced Errors[1]

Data Item	Error Units	Nominal Error	CAP Data Exchange-Enhanced Error
Weight	%	10	2.5
Wind Forecast	kts	ARTCC -20.0	4.0
		TRACON - 4.7	TRACON - 4.0
Temp Forecast	°C	10	1

[1]Error are assumed to be unbiased, i.e., mean values are assumed to be zero.

In the case of the CAP weight data error, a separate analysis of historical aircraft weight data by American Airlines was performed to validate the Seagull estimate. Using the FAA's Post Operations Evaluation Tool (POET), American Airlines analyzed planned and actual landing weight data for DFW arrivals. The data analyzed was for September 18-October 1, 1998, for which DFW experienced good weather. The mean and standard deviation between the AOC-planned and actual landing weight were calculated to be -0.462% and 1.78%. The standard deviation was observed to be a strong function of equipment type and is expected to be higher under bad weather conditions. CAP data exchange of AOC predictions of aircraft weight before TOD will likely be more accurate.

The resulting 1.78% standard deviation validated the Seagull weight standard deviation estimate as being a reasonable, albeit conservative, estimate.

The error data from Table 10-6 was used in the Trajectory Accuracy and Traffic Spacing model, to generate expected arrival metering fix delivery accuracies and average expected values of the runway threshold excess spacing buffers. The averaging of the expected spacing buffer values were performed using weighting based on pairwise aircraft occurrence distributions that are a function of airport fleet-mix. For the current analysis, a fleet mix based on DFW operations was used. The results from the Trajectory Accuracy and Traffic Spacing model in terms of expected values of CTAS performance metrics are shown in Table 10–7.

Table 10-7 Nominal and CAP Data Exchange-Enhanced CTAS Performance[2]

CTAS Performance Metric	Nominal Data	CAP Data Exchange Data[3]
Metering Fix Delivery Accuracy (sec)	54	21
Runway Threshold Excess Spacing Buffer (sec/nmi)	23.54 sec 0.82 nmi	23.02 sec 0.81 nmi

[2]EDA and A-FAST advisories are assumed to be used by controllers in both cases.

[3]60-75% of this buffer was due to the weight exchange and the rest was due to the improved wind/temp forecasts.

The CAP data exchange is expected to improve the MF delivery accuracy by roughly 30 seconds. Although weight has a negligible impact on timing accuracy, it is expected to have larger impacts on trajectory accuracy which would allow benefits of more fuel efficient descents and reduced ATM interruptions through improved conflict probe accuracy. Moreover, the primary benefit of improved MF delivery accuracy is fuel efficiency gains, improved distribution of delay between ARTCC and TRACON airspaces, and only secondary impact on arrival threshold buffer values. One assumption worth noting is that the use of the Trajectory Accuracy and Traffic Spacing model assumed weight exchange participation by all arrival air traffic, and the metering fix delivery accuracy will degrade with lower levels of data exchange. However, for congested major hub airports, levels of participation will approach full participation. For example, Appendix G identifies 70.4% of 1996 DFW annual operations to be itinerant air carrier and 26.3% of operations to be itinerant commuter - both classes of aircraft to be likely participants in CAP weight data exchange.

The threshold buffer is expected to reduce by 0.5 seconds or 0.01 nmi due to CAP data exchange, which will result in increased runway throughput and decreased flight delays. As in the case of the weight exchange, the use of the Trajectory Accuracy and Traffic Spacing model assumed wind and temperature forecast data exchange participation by all arrival air traffic. However, the increase in CTAS trajectory prediction accuracy due to aircraft-sensed wind and temperatures is not expected to be closely correlated to the level of data exchange participation (as long as a significant number of arrival aircraft are participating). Therefore, the calculation of potential threshold buffer reduction delay savings were assumed to be independent of level of data exchange participation. The delay savings due to this reduced threshold buffer was calculated in the following manner.

The expected spacing buffer calculated was first used with previous benefit analysis operations data to generate the aircraft delay savings due to the CAP weight and airborne wind and temperature data exchange mechanisms at the 10 study airports. The expected spacing buffers were used in conjunction with previously-generated data (see Figures 4-2 and 4-3 in Reference 15) that represented the relationship of average delays to spacing buffers as a function of IFR versus VFR and departures versus arrivals for the 10 airports.

Data for 1996 and 2005 level of operations were used in generating the average CAP data exchange delay savings for 1996 and 2015, respectively. Therefore, the savings for 2015 should be a conservative estimate. The final CAP Data Exchange delay savings for IFR and VFR departures and arrivals for the 10 study airports in the 1996 and 2015 time frames are shown in Table 10-8.

Table 10-8 1996/2015 CAP Data Exchange Delay Savings for 10 Airports

	Average Aircraft Delay Savings (minutes/operation)							
	1996				2015			
	IFR		VFR		IFR		VFR	
Airport	Depart	Arrival	Depart	Arrival	Depart	Arrival	Depart	Arrival
DEN - Denver	0.02	0.03	0.00	0.01	0.02	0.04	0.01	0.01
DFW - Dallas-Ft. Worth	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
EWR - Newark	0.14	0.16	0.01	0.01	0.11	0.15	0.06	0.10
JFK - N.Y. Kennedy	0.00	0.01	0.02	0.03	0.01	0.01	0.04	0.06
LAX - Los Angeles	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
LGA - N.Y. LaGuardia	0.10	0.12	0.94	0.95	0.14	0.18	0.89	0.92
MSP - Minneapolis	0.17	0.26	0.10	0.13	0.15	0.19	0.11	0.11
ORD - Chicago O'Hare	0.00	0.00	0.14	0.20	0.08	0.11	0.42	0.41
PHL - Philadelphia	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
SFO - San Francisco	0.08	0.07	0.14	0.13	0.08	0.03	0.14	0.37

The results from Table 10-8 were then converted into annualized savings by applying the airport cost rates from Appendix G, calculating the average cost savings assuming 50% of the operations are arrivals, multiplying the results by the annual IMC and VMC operations (taken from Table 9-16) and summing the resulting IMC and VMC annual savings. The final results in annualized savings as a function of meteorological conditions and year are shown in Table 10-9.

Table 10-9 1996/2015 Annual CAP Data Exchange Economic Savings for 10 Airports

	Annual Economic Savings (1996$ million)					
	1996			2015		
Airport	IMC	VMC	Total	IMC	VMC	Total
DEN - Denver	0.02	0.07	0.08	0.03	0.18	0.22
DFW - Dallas-Ft. Worth	0.12	0.19	0.31	0.42	0.56	0.98
EWR - Newark	0.31	0.10	0.40	0.41	1.30	1.70
JFK - N.Y. Kennedy	0.01	0.24	0.25	0.01	0.54	0.56
LAX - Los Angeles	0.71	3.33	4.04	0.78	5.96	6.74
LGA - N.Y. LaGuardia	0.16	6.87	7.03	0.29	8.10	8.39
MSP - Minneapolis	0.32	1.27	1.59	0.38	1.92	2.30
ORD - Chicago O'Hare	0.00	3.68	3.68	0.52	11.85	12.37
PHL - Philadelphia	0.01	0.53	0.54	0.02	1.05	1.07
SFO - San Francisco	0.12	1.55	1.67	0.13	4.99	5.12

Extrapolation to include the other 33 study airports was done by assuming the airport surrogate assignments previously assigned in Table 9-21. For each of the 33 study airports, the same level of CAP data exchange delay savings per operation as the assigned airport surrogate was used (see Table 10-10).

Table 10-10 1996/2015 CAP Data Exchange Delay Savings for 33 Airports

Average Aircraft Delay Savings (minutes/operation)

Airport	Surrogate Airport[1]	1996 IFR Depart	1996 IFR Arrival	1996 VFR Depart	1996 VFR Arrival	2015 IFR Depart	2015 IFR Arrival	2015 VFR Depart	2015 VFR Arrival
ATL - Atlanta	LAX	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
BDL - Bradley	DFW	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
BNA - Nashville	JFK	0.00	0.01	0.02	0.03	0.01	0.01	0.04	0.06
BOS - Boston	LAX	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
BWI - Baltimore-Wash	DFW	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
CLE - Cleveland	EWR/MSP [2]	0.14	0.16	0.01	0.01	0.15	0.19	0.11	0.11
CLT - Charlotte	MSP/EWR [2]	0.17	0.26	0.10	0.13	0.11	0.15	0.06	0.10
COS - Colorado Springs	JFK	0.00	0.01	0.02	0.03	0.01	0.01	0.04	0.06
CVG - Cincinnati	LAX	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
DAB - Daytona Beach	DEN	0.02	0.03	0.00	0.01	0.02	0.04	0.01	0.01
DCA - Washington Natnl	EWR/MSP [2]	0.14	0.16	0.01	0.01	0.15	0.19	0.11	0.11
DTW - Detroit	LAX	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
FLL - Ft. Lauderdale	PHL	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
HOU - Houston Hobby	PHL	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
HPN - Westchester Co.	DEN	0.02	0.03	0.00	0.01	0.02	0.04	0.01	0.01
IAD - Washington Dulles	DFW	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
IAH - Houston Intnl	MSP/EWR [2]	0.17	0.26	0.10	0.13	0.11	0.15	0.06	0.10
LAS - Las Vegas	PHL	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
LGB - Long Beach	DEN	0.02	0.03	0.00	0.01	0.02	0.04	0.01	0.01
MCO - Orlando	PHL	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
MDW - Chicago Midway	JFK	0.00	0.01	0.02	0.03	0.01	0.01	0.04	0.06
MEM - Memphis	EWR/MSP [2]	0.14	0.16	0.01	0.01	0.15	0.19	0.11	0.11
MIA - Miami	MSP/EWR [2]	0.17	0.26	0.10	0.13	0.11	0.15	0.06	0.10
OAK - Oakland	DFW	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
PDX - Portland	DFW	0.06	0.08	0.00	0.02	0.12	0.13	0.00	0.03
PHX - Phoenix	EWR/MSP[2]	0.14	0.16	0.01	0.01	0.15	0.19	0.11	0.11
PIT - Pittsburgh	MSP/EWR [2]	0.17	0.26	0.10	0.13	0.11	0.15	0.06	0.10
SAN - San Diego	JFK	0.00	0.01	0.02	0.03	0.01	0.01	0.04	0.06
SDF - Louisville	PHL	0.01	0.00	0.00	0.11	0.01	0.01	0.01	0.14
SEA - Seattle	EWR/MSP [2]	0.14	0.16	0.01	0.01	0.15	0.19	0.11	0.11
SLC - Salt Lake City	MSP/EWR [2]	0.17	0.26	0.10	0.13	0.11	0.15	0.06	0.10
STL - St. Louis	LAX	0.16	0.16	0.00	0.38	0.13	0.11	0.00	0.47
TEB - Teterboro	DEN	0.02	0.03	0.00	0.01	0.02	0.04	0.01	0.01

[1]Source: Table 9-21

[2]Airport#1/Airport#2 = Using 1996 results from Airport#1 and 2015 results from Airport#2.

The results from Table 10-10 were then extrapolated to annual savings using the same method as previously applied to the 10 airports. A summary of the annual savings for these 33 airports is shown in Table 10-11.

Table 10-11 1996/2015 Annual CAP Data Exchange Economic Savings for 33 Airports

	Annual Economic Savings (1996$ million)					
	1996			2015		
Airport	IMC	VMC	Total	IMC	VMC	Total
ATL - Atlanta	0.59	4.78	5.37	0.60	8.00	8.60
BDL - Bradley	0.03	0.03	0.06	0.08	0.06	0.14
BNA - Nashville	0.00	0.11	0.11	0.00	0.32	0.32
BOS - Boston	0.28	2.05	2.33	0.25	3.01	3.26
BWI - Baltimore-Wash	0.06	0.06	0.13	0.18	0.16	0.34
CLE - Cleveland	0.17	0.06	0.23	0.28	1.01	1.29
CLT - Charlotte	0.34	1.26	1.60	0.29	1.31	1.60
COS - Colorado Springs	0.00	0.09	0.09	0.00	0.27	0.27
CVG - Cincinnati	0.23	1.71	1.93	0.33	4.15	4.48
DAB - Daytona Beach	0.00	0.01	0.01	0.00	0.01	0.01
DCA - Washington Natnl	0.14	0.07	0.21	0.16	0.90	1.06
DTW - Detroit	0.41	2.79	3.20	0.53	5.83	6.36
FLL - Ft. Lauderdale	0.00	0.30	0.30	0.00	0.75	0.76
HOU - Houston Hobby	0.00	0.30	0.30	0.01	0.52	0.53
HPN - Westchester Co.	0.01	0.01	0.01	0.01	0.01	0.02
IAD - Washington Dulles	0.05	0.05	0.10	0.12	0.12	0.24
IAH - Houston Intnl	0.36	1.30	1.66	0.50	2.26	2.76
LAS - Las Vegas	0.00	0.81	0.81	0.00	2.12	2.12
LGB - Long Beach	0.01	0.01	0.02	0.01	0.02	0.03
MCO - Orlando	0.00	0.55	0.56	0.01	1.50	1.52
MDW - Chicago Midway	0.00	0.13	0.14	0.01	0.38	0.39
MEM - Memphis	0.13	0.08	0.21	0.24	1.55	1.78
MIA - Miami	0.08	1.67	1.75	0.08	2.03	2.10
OAK - Oakland	0.09	0.07	0.16	0.24	0.18	0.42
PDX - Portland	0.05	0.06	0.11	0.14	0.15	0.29
PHX - Phoenix	0.01	0.16	0.17	0.02	3.01	3.03
PIT - Pittsburgh	0.66	1.07	1.74	0.51	0.99	1.50
SAN - San Diego	0.00	0.16	0.17	0.01	0.52	0.53
SDF - Louisville	0.00	0.27	0.27	0.01	0.54	0.54
SEA - Seattle	0.26	0.09	0.35	0.46	1.70	2.16
SLC - Salt Lake City	0.11	1.01	1.13	0.12	1.28	1.40
STL - St. Louis	0.29	3.07	3.36	0.33	5.53	5.86
TEB - Teterboro	0.00	0.00	0.01	0.00	0.01	0.01

The total annual economic savings attributable to expected throughput increases and delay savings that result from CAP data exchanges were calculated by adding the total economic savings for all 43 target airports from Tables 10-9 and 10-11. The results are $48.2 millions/year for 1996 operations and $95.2 millions/year for 2015 operations. It should be reiterated that additional benefits would accrue from the additional mechanisms of a more efficient distribution of delay between ARTCC and TRACON airspaces, more fuel-efficient trajectories, and reduced ATM trajectory interruptions that would result from improved CAP-enhanced CTAS prediction accuracies.

Intra-Airline Slot Swapping

A future CAP two-way exchange of AOC and ATM information and supporting ATM and airline decision support tools are planned to enable intra-airline slot swapping. This slot swapping has the potential for providing additional airline benefits due to a number of benefit mechanisms that include, similar to the CTAS repeater, reduced ground personnel and equipment costs, reduced misconnections, reduced baggage mishandling costs, and reduced diversions. Quantitative CAP engineering analyses were performed to investigate the span of potential benefits provided by the intra-airline slot swapping.

For any given two aircraft inbound to a common destination airport, the value to an airline of exchanging their relative arrival time slots will depend on the relative importance of each flight's arrival times to airline operating revenue, cost, and resources, and any potential costs incurred by performing the swap. The swap of two aircraft flying at maximum range speeds for their given altitudes results in a fuel-burn penalty due to the accelerations and decelerations involved in the swap maneuver. The successful implementation of a desired swap will also be subject to constraints due to such factors as: aircraft flight mechanics; airspace geometry and restrictions, including weather and special-use airspace; ATC and AOC operational procedures; controller, pilot, traffic flow manager and dispatcher workload; aircraft fuel loads; and conflicting air traffic.

A key factor in potential slot swaps and their potential benefits is the maximum time difference between the arrival slots (i.e., times of arrival) of two aircraft to be involved in a swap. For two incoming arrival aircraft in en route airspace, two important cases would be those when both aircraft are airborne and i) no aircraft holding is in effect, and ii) aircraft holding is in effect. A first-order analysis of the maximum slot time differentials that result from these two cases is now discussed. {Note: we will neglect the cases where one or more of the aircraft are on the ground. One such case would be the case when one or both of the swapping aircraft is a satellite airport departure (i.e., the flight origin is within the 250 nmi outer arc CTAS TMA planning horizon) bound for the arrival airport. These cases are likely to be small in number, but probably offer some of the greatest potential slot time differentials.}

Maximum Slot Time Differential: No Aircraft Holding -- A typical slot swap involving no aircraft holding would occur between two aircraft where one of the aircraft is flying at a long-range (i.e., minimum fuel burn) cruise speed and the other aircraft would be flying at its maximum normal operating speed, V_{mo}. The resulting maximum slot time differential would be a function of a number of factors including the aircraft locations, aircraft equipment types involved, atmospheric properties (e.g., winds and temperatures), current air traffic management procedures, the time-to-fly and distance away from the destination airport at which a slot swap is initiated, and the respective aircraft flight plans.

To obtain a rough-order-of-magnitude estimate of a typical maximum slot time differential, a scenario was analyzed involving two McDonnell-Douglas MD-80 aircraft on straight-line "direct to destination" flight plans with both of them initiating their slot swap as they are 250 nmi out from the destination and ending their slot swap at the inbound metering fix (due to traffic congestion concerns) at a distance 30 nmi out from the destination. The effects of winds, en route congestion, arrival scheduling, and vertical flight profile were ignored. Both aircraft are initially flying at a typical long-range cruise speed of M=0.75 (which at 30,000 feet during a standard day would be equivalent to a true airspeed of 442 kts). Before initiation of the slot swap, one aircraft is directed to immediately slow down to 250 kts until the metering fix and the other is directed to speed up to its maximum operating speed of 500 kts, until a quick deceleration to 250 kts at the metering fix. Their arrival slots are assigned based on their estimated times en route. In this maximum slot time differential scenario, because of airline preferences, the airline controlling the two aircraft desires that these two aircraft perform a slot swap.

Using an approximate method similar to previous time-to-fly analyses [ref.18], the difference in the two aircraft's time-to-fly to the metering fix, ΔT, can be expressed as:

$$\Delta T = TTF_{slow} - TTF_{fast}$$

and,

$$TTF_{slow} = \frac{D}{V_{slow}} - \left(\frac{V_{lrc}^{2} - V_{slow}^{2}}{2aV_{slow}} \right) + \left(\frac{V_{lrc} - V_{slow}}{a} \right)$$

and,

$$TTF_{fast} = \frac{D}{V_{mo}} + \frac{(V_{mo} - V_{slow})^2}{2aV_{mo}}$$

where,

TTF_{slow} is the time-to-fly to the metering fix for the slow aircraft,

TTF_{fast} is the time-to-fly to the metering fix for the fast aircraft,

V_{slow} is the speed to which both aircraft must decelerate to at by the metering fix (the slow aircraft decelerates immediately and the fast aircraft decelerates at the end,

V_{lrc} is the aircraft long range cruise speed,

V_{mo} is the aircraft maximum operating speed,

D is the distance between the initial aircraft positions and the metering fix, and

a is the value of constant deceleration to V_{slow}.

Using our previously-assumed values of V_{slow}=250 knots, V_{lrc}=442 knots, V_{mo}=500 knots, and D=250-30=220 nmi, and assuming an initial instantaneous acceleration for the fast aircraft to V_{mo} and decelerations of the respective aircraft by a typical value of a=1 kts/sec [ref.18], we obtain TTF_{slow} = 51.6 minutes, TTF_{fast} = 27.4 minutes, and a maximum slot time differential of approximately *24* minutes. Typical values of this slot differential will typically be lower with finite aircraft accelerations to the higher speeds and the likelihood that one of the aircraft is already significantly closer than the 250 nmi boundary , but this differential may approach the 24 minute level if CAP technology allows slot swaps to start when aircraft are further out, terminal arrival routes are very indirect or if aircraft have faster V_{mo}'s.

<u>Maximum Slot Time Differential: Aircraft Holding</u> -- A second interesting case for CAP-enabled slot swaps is the case where aircraft are in holding patterns outside a congested terminal area and a slot swap is desired by an airline between two aircraft heading for or already in the holding pattern. In the case of a slot swap between two aircraft heading for or already in a holding pattern, time required in the holding pattern will lengthen the maximum slot time differential above that in the non-holding case. If holding time gets long enough, the slot time differential will be limited by the fuel on board the aircraft. According to FAR 121.639, domestic air carriers flights may only be dispatched if they have enough fuel: a) to fly to its destination airport, b) to fly to and land at the most distant alternate airport, and c) to fly for an additional holding time of 45 minutes at normal cruising fuel consumption. Any other amount of fuel on board, dependent on airline policy and pilot preference, is usable as additional holding fuel. Discussions with AAL dispatchers elicited the fact that in very bad weather conditions, dispatchers will put on additional holding fuel for as much as 2 hours of holding. In this holding scenario, then, the maximum slot differential time will depend on the current level of holding, the holding fuel on each of the aircraft on board, and how far ahead

of one another the aircraft entered the holding pattern. Regardless, the maximum slot time differential of 2 hours is significantly more than in the non-holding case and, correspondingly, this holding case will offer potentially more benefits to the airline per swap due to the additional schedule controllability. However, the frequency of such holding scenarios will be significantly less than that of non-holding ones.

Arrival Slot Swapping Potential Benefits Evaluation -- Discussions among American Airlines operations coordinators, operations analysts, and ramp personnel deemed that a quantitative estimate of the potential benefits of arrival slot swapping would require an in-depth look at historical operational data. Because no operational experience with such an advanced concept exists, it is difficult for airline operational personnel to estimate with any level of reliability what the potential benefits might be. The potential benefits will be tied to default arrival flight schedules and sequences, specific airline policies and preferences, and slot time differential constraints based on operational and aircraft performance factors. The complex, tactical nature of the potential benefits makes high-level estimation of annualized benefits quite difficult. Therefore, the only near-term approach that was deemed reliable was a real-time playback of historical AAL data using their T-DECS operational system. Unfortunately, the current level of airline effort did not allow for such a study. However, from a qualitative standpoint, such arrival slot swapping should offer additional benefits beyond the CTAS repeater benefits due to the additional degree of airline arrival control. In general, the quantitative benefits will include additional available economic benefits from the mechanisms previously mentioned for the CTAS repeater (i.e., reduced ground personnel and equipment, reduced misconnections, reduced baggage mishandling costs, and reduced low-fuel diversions), as well as reduced fuel burn and delays from reduced ground congestion - due to smoother arrival flows. However, due to the more sophisticated decision support tool technology involved, it is likely that the fielding of such tools will tend to be more limited than other CAP functionalities and only be done where the economic benefits are highest (i.e., for airspace around major hub airports).

Summary of CAP Benefits

At this point in time, our best ability to conservatively estimate the potential benefits of CAP for the 43 target airports in this study results in a rough-order-of-magnitude estimate of $50+ millions per year for 1996 and $100+ millions per year for 2015. However, many benefit mechanisms for all of the CAP functionalities remain to be assessed and it is too early to draw any firm conclusions about the total or relative potential benefits of the different CAP functionalities.

Broken down into different levels of CAP functionality, the benefits calculated are shown in Table 10-12.

Table 10-12 Rough-Order-of-Magnitude Estimated CAP Benefits for AAL Operations

	Nationwide Airline Savings ($millions/year)	
CAP Functionality	1996	2015
CTAS-to-Airline Data Exchange	>5.8	>9.0
Airline-to-CTAS Data Exchange	>48.2	>95.2
Intra-Airline Slot Swapping	Unknown, >0	Unknown, >0
TOTAL	50+	100+

These numbers should be on the low side because of our conservative estimation approach, the significant number of unknowns in terms of CAP technology, its technical performance, and the specific ability of the airlines to improve their decision-making through usage of the CAP tools, and a significant number of benefit mechanisms that could not be quantitatively assessed in this effort.

In general, the preliminary benefits associated with Airline-to-CTAS data exchanges tend to be significantly higher than those associated with CTAS-to-Airline data exchanges. For the benefit mechanisms quantified, a major reason for this difference seems to be with the tendency for CTAS-to-Airline data exchanges to provide significant economic benefits during off-nominal events such as low-fuel diversions or baggage misconnections. In the case of Airline-to-CTAS data exchange, the benefits are much smaller per event, but these nominal events are of very high frequency and result in higher total economic values.

In this effort to quantitatively estimate the potential benefit of CAP, a number of difficulties were encountered including the preliminary nature of CAP technology and its limited use in the airline operational environment, the complexity of evaluating reductions in passenger misconnections, the inability to quickly investigate airline operational details, and a dearth of existing detailed modeling tools designed to evaluate the impact of CAP-type technology on airline operations. On the other hand, we identified a multitude of potential qualitative benefit mechanisms for CAP and some NASA-obtained field test evidence that there are benefits to be accrued in the operational environment.

In the area of CAP benefits analysis, significantly more work remains to be done, especially in the area of detailed airline operational analysis work. Promising near-term methodologies to assist in the estimation of CAP benefits, in addition to those used in this study, include real-time simulation using airline operational play-back capabilities and rigorous field test assessments.

Engineering Analysis of Noise Impact

(contributor: R. Simpson, Flight Transportation Associates, Inc.)

The impacts of noise occur from operation of the approach and departure paths close to the ground and within a few miles of the runways. If these paths are changed due to better navigation and guidance, and better DSTs then these impacts will change. The primary impact today comes from the takeoff paths when the aircraft is using full power. For landing, there would seem to be a need to continue today's practice, of allowing aircraft to become established on shallow, straight-line approach paths at least a few miles from the runway to ensure a safe approach and touchdown. At many airports, there is a constant question of the safety of proposed noise abatement paths as suggestions are made to have aircraft maneuver both laterally and vertically shortly after takeoff, and shortly before touchdown. Note that if the paths remain similar, and DSTs decrease the spacing of successive operations, the noise impact is not beneficial, and the community would be aroused to place a traffic operations limit based on noise impacts on the airport. This Noise Capacity has already occurred at Schiphol in the Netherlands, Munich in Germany, and Sydney, Australia. This type of action would prevent the benefits which might be ascribed to DSTs.

At major urban airports in the US and elsewhere, there are a wide variety of noise restrictions on the usage of the runways which usually constrains runway capacity by reducing the number of active runways, restricting their use by certain types of aircraft, closing their use during evening an night hours, etc. The situation at each airport is different, and to study the possible impact of new types of approach and departure paths available from new DSTs would require a detailed study of these restrictions and their importance to the annual capacity at that airport. It is not known what the political response might be at each noise impacted airport. There is an ever changing situation among the various local parties who determine how airport noise is handled when new approach and departure procedures are proposed. Even when noise beneficial procedures can be proposed, the local community representatives often may not agree to anything which allows more aircraft to use the airport. Their hope is to drive traffic elsewhere, and to cause a new airport to be built to share the traffic in a given urban area.

Engineering Analysis of Emissions Impact

(contributors: R. Simpson, R. Ausrotas, Flight Transportation Associates, Inc.)

The impacts of engine exhaust emissions vary with the phase of flight. There is global concern about the impacts at high altitudes which depends on the total amount of flying being done in future years by engines with different exhaust characteristics. The impact is controversial and uncertain, and may not be significantly influenced by terminal airspace DSTs in this high altitude area.

At lower altitudes, aviation exhaust plays a minor role in major urban areas relative to the emissions of automobiles and trucks. The benefits can be estimated if newer procedure for arrival and departure at an airport can be shown to save fuel since the consumption of fuel provides the exhaust emissions. Any estimate of fuel savings below some altitude (such as 3000 feet) due to efficient arrival and departure procedures based on new DSTs can be translated to an equivalent reduction in emissions.

Of particular importance to the Environmental Protection Agency (EPA) are emissions in that portion of the atmosphere (earth surface to 900m/3000 ft, known as the mixing zone) where the landing and takeoff (LTO) cycle takes place. This is the area where emissions affect ground level pollutant concentrations. The EPA [ref.50] defines the LTO cycle as those aircraft operations below 3000 ft that begin when the aircraft approaches the airport on its descent from cruising altitude, lands and taxis to the gate. It continues as the aircraft taxies back out to the runway for subsequent takeoff and climbout to cruising altitude. Thus the five operating modes in an LTO are:

Approach (30% takeoff thrust, 4.0 minutes)

Taxi/idle-in (7% takeoff thrust, 7.0 minutes)

Taxi/idle-out (7% takeoff thrust, 19.0 minutes)

Takeoff (100% takeoff thrust, 0.7 minutes)

Climbout (85% takeoff thrust, 2.2 minutes)

The impact of DSTs on aircraft emissions of interest to the EPA is limited to the LTO cycle. Since the nominal LTO cycle lasts 32.9 minutes, only a small portion of overall aircraft emissions takes place during this time. For example, for a typical short haul flight(900 km), 20% of the overall oxides of nitrogen (NOx) emissions take place below 900m; for a long haul flight (8500 km), the emissions are 5.2%.

In the future, as airline fleets are upgraded, engine emission rates will continue to decrease. These reductions could possibly be balanced by continued growth in air travel. As patterns of airline operations change (growth or decrease in hub operations, for example), the changes in air quality will be highly site specific.

11. Findings

DST Benefits -- The quantitative analysis results support the functional descriptions of DST potential benefits impacts discussed in the Sections 2 through 7 of this report and summarized below.

Single-Center and Multi-Center TMA contributes to more efficient runway system utilization by establishing optimized runway allocations and generating schedules and advisories for aircraft crossing the metering fix. Delay absorption advisories displayed to Center air traffic controllers are used to maneuver aircraft so that actual metering fix crossing times conform closely with the TMA schedule. An improved arrival time delivery accuracy at the metering fix relative to current operations is achieved, resulting in a reduction in the variance between the actual and predicted trajectories. More fuel efficient trajectories are a direct result of TMA's delay distribution function which diverts a proportion of flight delay from TRACON to Center airspace, reducing fuel burn without impacting runway system throughput and overall delay.

pFAST determines efficient runway assignments, sequences and schedules for terminal area arrival aircraft, and displays the corresponding landing runway assignment and sequencing advisories to TRACON controllers. pFAST enables controllers to better utilize the runway and airspace system relative to current operations through reduced aircraft position uncertainty and improved runway balancing and aircraft trajectory sequencing. The improved controllability of spacing between successive aircraft effectively achieves a reduction in the excess spacing buffer. The pFAST runway balancing process increases system efficiency by assigning aircraft to the runway that minimizes overall delay. Improved trajectory sequencing integrates the terminal airspace arrival process with the runway system optimization plan, reinforcing the elimination of extraneous gaps at the runway so as to maintain a steady stream of landings.

aFAST enhances the pFAST runway assignment, sequencing, and scheduling functionality by displaying timely airspeed and heading advisories to controllers which are specifically directed to accurately positioning and spacing aircraft on terminal airspace arrival patterns, especially the final approach. Benefits derived from aFAST are analogous to those of pFAST, but with greater improvement impact. aFAST further reduces the variance between actual and planned aircraft position, reducing spacing buffer and extraneous gaps, and improves runway balancing and sequencing operations to reduce delay.

CAP provides airlines with timely updates of arrival time and terminal area delay predictions which allow for improved airline decision-making. Airlines can use the CAP information to improve ground personnel and equipment utilization, reduce baggage mishandling costs, reduce misconnections, reduce low-fuel diversions, and make better scheduling decisions. Additionally, CAP provides airline-sensed flight and weather information to CTAS to improve CTAS trajectory prediction accuracy. These trajectory prediction accuracy improvements will result in: reduced runway threshold spacing buffers which will lead to delay savings, better CTAS metering fix delivery accuracy which will lead to improved TRACON-Center delay distribution and more fuel efficient descent trajectories, and improved conflict detection accuracy which will lead to reduced ATM interruptions. Also, CAP provides decision support tools to support ATM and airline collaboration that will enable more airline control of arrival trajectories that will include concepts such as intra-airline slot swapping. These decision support tools will allow airlines to increase their control of flight arrival schedules and sequences, thereby enhancing schedule integrity, improving personnel and equipment utilization, and reducing inefficiencies such as misconnections and diversions.

EDP expands the functionality of TMA-FAST by including departures and multiple airport operations in the development of strategies to optimize traffic movement. The management of overtaking, crossing and merging situations involving arrivals and departures is improved by EDP-generated sequencing and spacing advisories which enable reduced spacing buffers. Runway system utilization is improved by simultaneously accounting for both arrival and departure traffic sequencing and spacing requirements. Improved trajectory control with EDP may enable controllers more frequently to approve expedited climbs with user-preferred speed and departure profiles. Integrated traffic planning by EDP would coordinate gate departure, runway takeoff and departure fix crossing scheduling to reduce ground and airspace delay and would facilitate the merging of satellite airport departures with the traffic flow of the major airport.

Traffic Data -- A review of the Government-furnished traffic data found several factors that should be considered with respect to the modeling methodology employed.

The 1996 daily traffic loadings for the 10 study airports furnished for use in this study are significantly lower than the traffic loadings used in a previous study [ref.15] of CTAS potential benefits. Table 11-1 shows the furnished 1996 traffic data generally account for 85% of the previously-used 1996 traffic demand. Also, the previous study used 2005 traffic forecasts, but these 2005 traffic levels are roughly the same as the furnished 2015 traffic forecasts by airport as shown in Table 11-1. Lower traffic demand would generate lower flight delay estimates, and would result in lower DST-based delay savings estimates relative to current operations.

Table 11-1 Daily Traffic Count by Airport Comparison

		1996 Traffic Count (Number of Daily Operations)									
Year	Data	DEN	DFW	EWR	JFK	LAX	LGA	MSP	ORD	PHL	SFO
1996	Previous	1394	2466	1256	973	2283	1023	1454	2565	1203	1267
1996	Furnished	1213	2164	1170	859	1943	927	1229	2152	974	1099
2005	Previous	1663	3154	1398	1101	2549	1023	1489	2649	1312	1612
2015	Furnished	1613	3246	1647	997	2211	1117	1723	2671	1420	1659

With reference to the furnished data, the 1996 and especially the 2015 traffic samples are characterized by situations in which a relatively long series of takeoffs (e.g., 10 successive departures), or a series landings, are scheduled to occur simultaneously. This spiking phenomena would hinder the interleaving of arrivals and departures in the modeling process, generating unrealistically large delays for certain crossing and parallel runway configurations. To resolve this issue, a special takeoff and landing sequence adjustment is applied in the IAT Model to avoid excessive delay intrusions due to instantaneous flight batching in the baseline schedule. However, this adjustment tends to pack flights unto the runway system regardless of current or DST operation such that the current system operation may be overly-optimistically represented relative to the DSTs.

Annual Cost Savings Extrapolations -- The extrapolation of cost savings to the non-study sites are highly dependent on the aircraft class mix at each site. Those sites with a high proportion of general aviation aircraft would have relatively low savings extrapolations because of the lower aircraft operating costs relative to sites serving predominantly air carriers.

Conclusions

The following observations concerning TMA, pFAST, aFAST and EDP are made based on the modeling results obtained for the 10 study sites.

TMA improvements in trajectory prediction and control accuracy support increased arrival airspace and runway system throughput as a result of reduced spacing dispersions between aircraft pairs along en route arrival trajectories and at the metering fix relative to the current system. This improved metering fix delivery accuracy would also enhance the capability of CTAS-based ATM to better distribute delay between Center and TRACON airspace.

- The estimated aircraft operating cost savings associated with reduced arrival airspace and runway system delay due to TMA with a 100 second maximum TRACON delay absorption restriction, based on 1996 traffic forecasts, range from $3.72 to 16.78 million annually for the 10 study sites and $2.82 to 29.31 million annually for the 2015 traffic forecasts.
- Total estimated TMA delay savings benefits for all 10 sites are $91.21 million and $121.52 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total TMA delay savings benefits in respective order of magnitude are SFO, ORD and LAX in 1996, and LAX, DFW, and ORD 2015.
- When TRACON delay absorption is unrestricted, aircraft would consume a greater proportion of their delay in the more fuel-efficient Center airspace rather than the TRACON airspace without impacting runway throughput and total delay. Otherwise, the available TRACON delay absorption capability would be best used to absorb metering fix delivery variability in order to maximize runway system throughput.
- TMA estimated incremental aircraft fuel cost savings due to delay distribution at all 10 airports under study with a 100 second maximum TRACON delay absorption restriction are zero.
- Based on previous study results,[ref.15] TMA estimated incremental aircraft fuel cost savings due to delay distribution with a 200 second maximum TRACON delay absorption restriction, could be at least 10% of the savings due to reduced runway system delay.

pFAST improvements in arrival trajectory prediction and control accuracy in association with improved arrival sequencing and runway assignment enable reductions in excess spacing buffers between aircraft pairs along terminal area arrival trajectories and at runway thresholds relative to the current system. The resulting increases in arrival airspace and runway system throughput generates reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced arrival airspace and runway system delay due to pFAST at 10 airports under study range from $0.41 to 42.47 million annually based on 1996 traffic forecasts and $1.39 to 61.18 million annually based on 2015 traffic forecasts.
- Total estimated pFAST benefits for all 10 sites are $85.66 million and $241.62 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total pFAST delay savings benefits in respective order of magnitude are ORD, SFO and LAX in 1996, and ORD, EWR and LAX in 2015.

aFAST improvements in arrival trajectory prediction and control accuracy in association with improved arrival sequencing and runway assignment enable further reductions in excess spacing buffers between aircraft pairs along terminal area arrival trajectories and at runway thresholds relative to the current system. The resulting increases in arrival airspace and runway system throughput generates further reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced arrival airspace and runway system delay due to aFAST at 10 airports under study range from $0.76 to 61.55 million annually based on 1996 traffic forecasts and $1.9 to 84.5 million annually based on 2015 traffic forecasts.
- Total estimated aFAST benefits for all 10 sites are $134.57 million and $343.02 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total aFAST delay savings benefits in respective order of magnitude are ORD, SFO and MSP in 1996, and ORD, LAX and EWR in 2015.

EDP improvements in departure trajectory prediction and control accuracy in association with improved arrival and departure sequencing and runway assignment enable reductions in excess spacing buffers between aircraft pairs along en route and terminal area departure trajectories and at runway thresholds relative to the current system. The resulting increases in departure and arrival airspace and runway system throughput generates further reductions in aircraft delay and operating costs.

- The aircraft estimated operating cost savings associated with reduced departure and arrival airspace and runway system delay due to EDP at 10 airports under study range from $6.83 to 96.91 million annually based on 1996 traffic forecasts and $12.23 to 173.13 million annually based on 2015 traffic forecasts.
- Total estimated EDP benefits for all 10 sites are $277.92 million and $722 million annually in 1996 and 2015, respectively.
- The top three airports accounting for total EDP delay savings benefits in respective order of magnitude are ORD, SFO and LAX in 1996, and ORD, LAX and EWR 2015.

The modeling of current and DST operations develops a runway utilization schedule and assignment plan assuming knowledge of the exact sequence of actual departures. In fact, the current system does not have such specific pre-takeoff data defining the actual departure traffic. TMA, pFAST and aFAST process data for arrival operations, but could be enhanced with pre-takeoff departure traffic data subject to system design and implementation. Because EDP integrates arrival and departure planning, the benefits of EDP may be understated relative to current operations and, depending on implementation, the other DSTs.

The pFAST, aFAST and EDP delay savings are highly sensitive to the IMC and VMC runway system configurations assumed at each airport.

The following observations concerning CAP are made based on engineering analysis results.

A conservative estimate of the potential benefits of CAP for 43 airports in this study results in a rough-order-of-magnitude estimate of $50 million per year for 1996 and $100 millions per year for 2015. In general, the preliminary benefits associated with Airline-to-CTAS data exchanges tend to be significantly higher than those associated with CTAS-to-Airline data exchanges:

- Airline-to-CTAS estimated annual savings are $48.2 million and $95.2 million in 1996 and 2015 respectively.
- CTAS-to-Airline estimated annual savings are $5.8 million and $9 million in 1996 and 2015 respectively.

The lower CTAS-to-Airline data exchange benefits would be due to the tendency for CTAS-to-Airline data exchanges to provide significant economic benefits during off-nominal events such as low-fuel diversions or baggage misconnections. In the case of Airline-to-CTAS data exchange, the benefits are much smaller per event, but these nominal events are of very high frequency and result in higher total economic values.

The CAP savings values shown above may be on the low side because of our conservative estimation approach, the significant number of unknowns in terms of CAP technology, its technical performance, and the specific ability of the airlines to improve their decision-making through usage of the CAP tools, and a significant number of benefit mechanisms that could not be quantitatively assessed in this effort.

Analysis Considerations and Recommendations

This study uses a new, advanced modeling capability, the Integrated Air Traffic Model, to evaluate potential aircraft operating cost savings due to the implementation of terminal airspace DSTs. The

IAT Model currently evaluates traffic loading, capacity and delay characteristics of operations in the extended terminal airspace and runway system associated with a single study airport.

Various useful expansions to the analytical scope of the IAT Model were evident during its application in this study. The model structure is extendible to realistically emulate multi-airport regional operations such as the US Northeast Corridor and other high-density domains. The value of this extension is exemplified by the individual analysis in this study of a subset of airports (i.e., JFK, LGA, EWR, and PHL) which share common arrival and departure fixes. This multi-airport network modeling function would include the capability to evaluate of satellite airport operations Also, the development of a airport network-based IAT Model could be directed to nationwide coverage.

The current IAT Model examines airspace trajectory and runway system operations, incorporating the salient capabilities of the trajectory accuracy and standard runway utilization modeling. The trajectory component tracks and optimizes scheduling, sequencing and spacing factors at discrete fixes. A logical extension in scope is the incorporation of continuous trajectory modeling to capture in more detail the operational dynamics associated with conflict detection and resolution maneuvers.

The IAT Model is a fast-time software simulation that is undergoing initial development, and is subject to review and verification. The model structure is designed to allow for numerous sophisticated features which are in various states of implementation. These features include:

- user preferred trajectories/flight plans
- potential conflict intervention alternatives
- alternative arrival and departure procedures
- alternative runway configurations and utilization procedures
- delay distribution optimization
- arrival and departures delay balancing
- excessive airborne arrival delay restrictions
- time-based vs. distance-based (miles-in-trail) metering
- flight performance characteristics
- time-varying meteorological conditions (IFR-VFR moving window)
- convective weather effects
- controller tasks and traffic handling capabilities
- Airline Operational Center (AOC) interactions with ATM

The IAT Model is a powerful and efficient mechanism for evaluating delay reduction, delay distribution optimization, trajectory optimization and related benefits corresponding to ATM enhancement and deployment alternatives for a variety of operational environments.

The limited time available to perform this study precluded extensive data sampling and collection, field experimentation, on-site observation and consultation, modeling and related investigations for each site. Many assumptions were necessary to develop preliminary estimates of potential benefits. An expansion of the scope and depth of the data collection and analysis procedures would facilitate a broad representation of and participation by the aviation community and lessen the dependence on analytical assumptions and extrapolations.

Appendix A -- Aircraft Type-Class Cross-Reference

Aircraft Type-Class Cross-Reference

Aircraft Class	1998 Type Designator	Manufacturer and Aircraft Model
2J/L	A10	Fairchild Ind. Thunderbolt II
2T/S	A109	Augusta Model A 109/A/A-II
2J/L	A3	McDonnell-Douglas Corp. Skywarrior
2J/H	A300	Airbus Ind. A300
2J/H	A310	Airbus Ind. A310
2J/LH	A320	Airbus Ind. A320
2J/H	A330	Airbus Ind. A330
4J/H	A340	Airbus Ind. A340
1J/S	A36	Construcciones Aeronauticas, A36 Halcon version of CASA C-101 Aviojet[2]
1J/L	A4	McDonnell Douglas Corp. Skyhawk
2J/L	A6	Grumman Aerospace Corp. Intruder, EA-6A[2]., EA-6B Prowler [2]
1P/S	AA1	Grumman Aerospace Corp. Yankee AA-1B/C, Trainer, T-Cat, Lynx[1]
1P/S	AA5	Grumman Aerospace Corp. Cheetah AA-5, Traveller, Tiger
1P/S	AA5	Grumman Aerospace Corp., AA-5A Cheetah[3]., AA-5B Tiger[3]
2P/S	AC50	Rockwell Int'l Corp. Commander 500
2P/S	AC56	Rockwell Int'l Corp. Commander 560
2P/S	AC68	Rockwell Int'l Corp. Super Commander 680S/E/F/FP
2P/S	AC6L	Rockwell Int'l Corp. Grand Commander 685/680FL
2T/S	AC6T	Rockwell Int'l Corp. Jet Prop Commander 840/980/1000
2P/S	AC6T	Rockwell Int'l Corp. Turbo Commander 690C/695/690/680T
2P/S	AEST	Piper Aircraft Corp. Aero Star 600/700
2P/S	AEST	Ted Smith Aerostar Corp. Aero Star[5]
2T/L	AN24RW	Antonov AN24RW Coke[2]
1T/S	AS50	Aerospatiale Ecurevil/Astar AS-350/550
2J/S+	ASTR	Israel Aircraft Ind. & Astra Jet Astra 1125
2T/L	ATP	British Aerospace Advance Turboprop (ATP), Jetstream 61
2T/L	ATR	Aerospatiale/Aeritalia ATR 42-200/300, ATR 72
1T/S	B06	Bell Helicopter Textron Jet Ranger/Long Ranger/Sea Ranger/Kiowa/Model 206, Combat Scout, TH-67 Creek[2]
SST	B1	Rockwell Int'l Corp. Lancer
2T/S	B12	Bell Helicopter Textron Twin Huey, Model 212, Model 214B/B-1, Model 412, Griffon
1P/S	B14A	Bellanca Aircraft Cruisair, Cruismaster 14-19
4P/L	B17	Boeing Co., B-17 Flying Fortress[4]
2T/S+	B190	Beech Aircraft Co. Beech 1900/C-12J
2T/S	B222	Bell Helicopter Textron Model 222, 230, 430
2P/L	B26	McDonnell-Douglas Corp. Invader
4J/H	B2A	Northrup /Grumman Stealth Bomber[2]
2T/S+	B350	Beech Aircraft Co. super King Air 350
8J/H	B52	Boeing Co. Stratofortress
4J/H	B707	Boeing Co. 707 (all series)
4J/H	B720	Boeing Co. 720B[6]
3J/L	B727	Boeing Co. 727 (all series)
2J/L	B73A	Boeing Co. 737/200 Series
2J/L	B73B	Boeing Co. 737-300/400/500 Series
2J/L	B73C	Boeing Co. 737-600/700/800 Series

4J/H	B74A	Boeing Co. 747-100/200/300 Series
4J/H	B74S	Boeing Co. 747SP/SUD
4J/H	B74B	Boeing Co. 747-400 Series
2J/LH	B757	Boeing Co. 757 (all series)
2J/H	B767	Boeing Co. 767 (all series)
2J/H	B777	Boeing Co. 777-200
2J/L	BA11	British Aerospace BAC One-Eleven
4J/L	BA46	British Aerospace Bae 146, Quiet Trader, Avroliner
2P/S	BASS	Beagle Aircraft, B.206 Bassett Series[1]
2T/S	BE10	Beech Aircraft Co. King Air 100/A/B (U-21F Ute)
1P/S	BE17	Beech Aircraft Co. Stagger Wing 17 (UC-43 Traveler)
2P/S	BE18	Beech Aircraft Co. Twin Beech 18., Super H18[3]
1P/S	BE19	Beech Aircraft Co. Sport 19, Musketeer 23
2T/S	BE20	Beech Aircraft Co. Super King Air 200/1300, Huron
2T/S	BE20	Beech Aircraft Co., Super King Air 200/1300, Huron[1], RC-12N Guardrail[3]
1P/S	BE23	Beech Aircraft Co. Sundowner 23, Musketeer 23
1P/S	BE24	Beech Aircraft Co. Sierra 24, Musketeer Super
2T/S+	BE30	Beech Aircraft Co. Super King Air 300
1P/S	BE33	Beech Aircraft Co. Bonanza 33, Debonair (E-24)
1P/S	BE35	Beech Aircraft Co. Bonanza 35
1P/S	BE36	Beech Aircraft Co. Bonanza 36
2P/S	BE50	Beech Aircraft Co. Twin Bonanza 50
2P/S	BE55	Beech Aircraft Co. Baron 55/Chochise
2P/S	BE58	Beech Aircraft Co. Baron 58, Foxstar
2P/S	BE60	Beech Aircraft Co. Duke 60
2P/S	BE65	Beech Aircraft Co. Queen Air 65 (U-8F Seminole)
2P/S	BE76	Beech Aircraft Co. Duchess 70
1P/S	BE77	Beech Aircraft Co. Skipper 77
2P/S	BE80	Beech Aircraft Co. Queen Air 80
2P/S	BE95	Beech Aircraft Co. Travelair 95
2T/S	BE99	Beech Aircraft Co. Airliner 99
2T/S	BE9L	Beech Aircraft Co. King Air 90, T-44A[3], C90B[3]A90 to E90 (t-44, V-C6), Taurus 90
2T/S	BE9T	Beech Aircraft Co. Beech F90 King Air
2T/S	BK17	MBB/Kawasaki Model BK 117
1P/S	BL17	Bellanca Aircraft Decathlon, Super Viking, Turbo Viking
1P/S	BL8	Bellanca Aircraft Decathlon, Super Decathlon
2P/S	BN2P	Britten Norman LTD. BN-2A/B Islander Defender
1P/S	C120	Cessna Aircraft Co. Cessna 120
4T/L	C130	Lockheed Corp., Hercules Model 382, 100 Series Commercial Hercules, Model 100-50 Hercules, Regional Air Freighter[1], Spectre
4J/H	C135	Boeing Co. Stratolifter B717, KC-135[1], KC-135E/R
4J/H	C141	Lockheed Corp. C-141 Starlifter
1P/S	C150	Cessna Aircraft Co. Cessna 150
1P/S	C152	Cessna Aircraft Co. Cessna 152
2T/L	C160	Nord Aviation Transall C-160
4J/H	C17	Boeing Co./ McDonnell Douglas Corp., Globemaster 3 C-17A[2]
1P/S	C170	Cessna Aircraft Co. Cessna 170
1P/S	C172	Cessna Aircraft Co. Skyhawk 172/Cutlass/Mescalero
1P/S	C175	Cessna Aircraft Co. Skylark 175
1P/S	C177	Cessna Aircraft Co. Cardinal 177
1P/S	C180	Cessna Aircraft Co. Skywagon 180 (U-17C) ., Skylane 182[1]
1P/S	C182	Cessna Aircraft Co. Skylane 182
1P/S	C185	Cessna Aircraft Co. Skywagon 185 (U-17A/B)
1P/S	C188	Cessna Aircraft Co., AGWagon/ AG Truck/AGHusky 188[1]

1P/S	C195	Cessna Aircraft Co. Cessna 195
2T/L	C2	Grumman Aerospace Corp. Greyhound
1P/S	C205	Cessna Aircraft Co. Super Skywagon/Super Skylane
1P/S	C206	Cessna Aircraft Co. Stationair 6, Turbo Stationair 6
1P/S	C207	Cessna Aircraft Co. Stationair/Turbo Stationair 7/8
1T/S	C208	Cessna Aircraft Co. Caravan 1 - 208, (Super) Cargomaster, Grand Caravan (U27)
1P/S	C210	Cessna Aircraft Co. Centurion 210, Turbo Centurion
2T/S+	C212	Construcciones Aeronauticas C-212 Aviocar
2T/S+	C26	Fairchild Aircraft Corp., C-26A military version of Metro[3]
2P/S	C303	Cessna Aircraft Co. Crusader 303
2P/S	C310	Cessna Aircraft Co. Cessna 310
2P/S	C320	Cessna Aircraft Co. Skynight 320
2P/S	C335	Cessna Aircraft Co. Cessna 335
2P/S	C336	Cessna Aircraft Co. Skymaster 336
2P/S	C340	Cessna Aircraft Co. Cessna 340
2P/S	C401	Cessna Aircraft Co. Cessna 401
2P/S	C402	Cessna Aircraft Co. Cessna 402
2P/S	C404	Cessna Aircraft Co. Titan 404
2P/S	C411	Cessna Aircraft Co. Cessna 411
2P/S	C414	Cessna Aircraft Co. Chancellor 414, Rocket Power
2P/S	C421	Cessna Aircraft Co. Golden Eagle 421
2T/S	C425	Cessna Aircraft Co. Corsair/Conquest I – 425
2T/S	C441	Cessna Aircraft Co. Conquest/Conquest 2 – 441
4J/H	C5	Lockheed Corp. C-5 Galaxy
2J/S	C500	Cessna Aircraft Co. Citation 1/SP
2J/S	C525	Cessna Aircraft Co. Citationjet C525
2J/S	C550	Cessna Aircraft Co. Citation 2/SP
2J/S+	C560	Cessna Aircraft Co., Citation 5[1]
2J/S+	C560	Cessna Aircraft Co. Citation 5
2J/S+	C650	Cessna Aircraft Co. Citation 3/6/7
1P/S	C72R	Cessna Aircraft Co. Cutlass RG, 172RG
2J/L	C9	McDonnell Douglas Corp/Boeing Co., Nightingale C-9A[2]., Skytrain 2 C-9B [2]
2J/L	CARJ	Canadair Bombardier LTD. Regional Jet
2J/L	CL60	Canadair Bombardier LTD. CL600/610 Challenger
1P/S	CM11	Rockwell Int'l Corp. Aero Commander 112, 114
1T/S	CM11	Rockwell Int'l Corp. Commander, 112TC
2T/S+	CN35	Airtech (CASA IPTN) CN-235M[6]
SST	CONC	Aerospatiale/British Aerospace Concorde
4P/L	CONI	Lockheed Corp. Constellation 649/749, Super Constellation, Starliner
1P/S	COUR	Helio Aircraft Co. H-295 Super Courier
2P/L	CVLP	General Dynamics Corp. Convair 240, 340, 440, Liner, Samaritan
2T/L	CVLT	General Dynamics Corp. Convair 540/580/600/640
2T/S+	D228	Dornier GmbH Do 228-200 Series
2T/L	D328	Dornier GmbH Do 328 Series
3J/H	DC10	McDonnell Douglas Corp. DC-10 (all series)
2P/S+	DC3	McDonnell Douglas Corp. Skytrain (C-47, C-53, C-117 A/B/C, R4D 1 to 7)
4P/L	DC4	McDonnell Douglas Corp. Skymaster
4P/L	DC6	McDonnell Douglas Corp. DC-6/B Liftmaster
4J/L	DC8	McDonnell Douglas Corp. DC-8 (all series), Jet Trader
2J/L	DC9	McDonnell Douglas Corp./Boeing Co. DC-9 Super/ Nightingale, Skytrain 2
1P/S	DG15	Howard, DG-15P, -15W, -15J[1]
1P/S	DHC2	Dehavilland Beaver DHC-2

1T/S	DH2T	DeHavilland, DHC-2T Turbo-Beaver
1P/S	DHC3	Dehavilland Otter DHC-3
2P/S+	DHC4	Dehavilland Caribou DHC-4
2T/L	DHC5	Dehavilland Buffalo DHC-5D/E
2T/S	DHC6	Dehavilland Twin Otter DHC-6 (all series)
4T/L	DHC7	Dehavilland DASH 7 DHC-7
2T/L	DHC8	Dehavilland DASH 8 DHC-8
2P/S	DO28	Dornier GmbH Do 28 A/B (Agur)
2T/S+	DO82	Dornier GmbH Do –228 Series
2T/S	E110	Embraer Bandeirante EMB-110/111
2T/S+	E120	Embraer Brasilia EMB-120
2T/L	E2	Grumman Aerospace Corp. Hawkeye E-2C[2], Daya
4J/H	E3	Boeing Co. E3 Sentry
4J/H	E6A	Boeing Co., E-6A TACAMO[2]
2T/S+	E9A	Bombardier Aerospace (DeHavilland) Dash 8Q Series 200 E-9A [2]
2J/LS	F100	Fokker BV Fokker 100
2J/L	F111	General Dynamics Corp. F-111/FB-111
2J/L	F117	Lockheed Corp., F117 A[3]
2J/L	F14	Grumman Aerospace Corp. Tomcat
2J/L	F14	Grumman Aerospace Corp. Tomcat[2], Super Tomcat[2]
2J/L	F15	McDonnell Douglas Corp. F-15 Eagle
1J/L	F16	General Dynamics Corp. Fighting Falcon
2J/L	F18	McDonnell Douglas Corp. F/A-18 Hornet
1T/S	F26T	SIAI Marchetti SpA SF260TP
2T/L	F27	Fokker BV Friendship F27, Troopship, Maritime, Firefighter
2J/LS	F28	Fokker BV Fellowship F28
3J/L	F2TH	Dassault-Breguet Falcon 2000[1]
2J/L	F4	McDonnell Douglas Corp. Phantom 2
2T/S	F406	Cessna Aircraft Co. Caravan 2 - F406
2J/L	F4G	McDonnell Douglas Corp. F4G Wild Weasel[3]
2J/S+	F5	Northrop Corp. Freedom Fighter Tiger II
2J/L	F70	Fokker 70[6]
1J/L	F86	Rockwell Int'l Corp. Sabre
3J/L	F900	Dassault-Breguet Falcon 900, Mystere 900 (T-18)
2J/S+	FA10	Dassault-Breguet Falcon10, Mystere 10
2J/S+	FA10	Dassault-Breguet Falcon 10, Mystere 10
2J/S+	FA20	Dassault-Breguet Falcon 20/C thru F, Fan Jet Falcon (FJF), Mystere 20 (T-11) , Mystere Falcon 200
3J/S+	FA50	Dassault-Breguet Falcon 50, Mystere 50 (T-16)
2T/S+	G159	Gulfstream Aerospace Corp. GAC 159-C, Gulfstream 1
2P/S+	G21	Grumman Aerospace Corp. Goose/Super Goose
2P/L	G222	Alenia, G222 Troop Transport[3]
2P/S+	G44	Grumman Aerospace Corp. Widgeon/Super Widgeon
1T/S	G520	Grob/Egrett, G-520 Trainer[3]
2P/S+	G73	Grumman Aerospace Corp. Mallard
2P/S	GA7	Grumman Aerospace Corp. Cougar GA-7
1P/S	GC1	Vought Corp. Swift
1P/S	GC1	Globe Corp. Swift GC-1B[4]
2J/L	GULF	Gulfstream Aerospace Corp. Gulfstream 2,3,4/5
2T/L	H2	Kaman Aerospace Corp., SH-2G Super Sea Sprite[3]
2J/S+	H25B	British Aerospace Bae HS 125 Series 700/800
2T/L	H46	Boeing Vertol Co. Sea Knight 107, CH-113, Labrador
2T/L	H46	Kawasaki Heavy Industries LTD. KV-107/II, Sea Knight, Labrador, Voyaguer, CH-113
2T/L	H47	Boeing Vertol Co. Chinook, Model 234., MH-47

2T/L	H53	Sikorsky Aircraft, Sea Stallion
2T/L	H53	Sikorsky Aircraft Sea Stallion S-65, Ch-53[3], Yasur, MH-53
2T/L	H60	Sikorsky Aircraft Black Hawk S-70, WS-70, VH-60[3]Seahawk, MH-60 Pavehawk, Rescue Hawk, Thunderhawk, Jayhawk, Ocean Hawk, Desert Hawk, Yanshuf, LAMPS MK3,
2T/L	H64	McDonnell Douglas Helicopters Model 77/Apache, Pethen, Longbow Apache
1J/L	HAR	British Aerospace Bae Harrier
1J/L	HAR	McDonnell Douglas/BAe AV-8B Harrier II[3]
2J/S+	HF20	Hamburger Flugzeubau HFB-320 Hansajet
2J/S+	HS25A	British Aerospace Bae HS 125 Series 1/2/3/400/600
1T/S	HUCO	Bell Helicopter Textron Cobra
1P/S	HUSK	Christen Industries Inc. A-1 Huskey
-	HXB	Homebuilt experimental aircraft, cruise speeds greater than 100 knots, but less than or equal to 200 knots[1]
-	HXC	Homebuilt experimental aircraft, cruise speeds greater than 200 knots[1]
4T/L	IL18	Illyushin IL-18 Coot[6]
4J/H	IL62	Ilyushin IL-62
4J/H	IL76	Ilyushin IL-76
4J/H	IL96	Ilyushin IL-96
1P/S	J2	Piper Aircraft Corp. Cub Trainer, J-2 Cub
2J/S+	JCOM	Rockwell Int'l Corp. Jet Commander 1121
2T/S+	JSTA	British Aerospace Bae Jetstream 31
2T/S+	JSTB	British Aerospace Bae 4100, Jetstream 41
3J/H	L101	Lockheed Corp. L-1011 Tri-Star (all series)
2P/L	L18	Lockheed Corp. Lodestar
4T/L	L188	Lockheed Corp. Electra 188
4J/L	L29A	Lockheed Corp. 1329 Jetstar 6/8
4J/L	L29B	Lockheed Corp. 1329-5 Jetstar 2/731
1P/S	LA25	Lake Aircraft LA-250 Renegade/Seafury
1P/S	LA4	Lake Aircraft LA-4/A/B, LA-4-200 Buccaneer
2J/S	LJ23	Gates Learjet Corp. Learjet 23
2J/S+	LJ24	Gates Learjet Corp. Learjet 24
2J/S+	LJ25	Gates Learjet Corp. Learjet 25,251
2J/S+	LJ28	Gates Learjet Corp. Learjet 28
2J/S+	LJ31	Gates Learjet Corp. Learjet 31
2J/S+	LJ35	Gates Learjet Corp. Learjet 35
2J/S+	LJ36	Gates Learjet Corp. Learjet 36
2J/S+	LJ55	Gates Learjet Corp. Learjet 55
2J/S+	LJ60	Gates Learjet Corp. Learjet 60
1P/S	M20	Mooney Aircraft Corp. Mark 20/M20J/21/200/201/202/205/220/ 231/252, Mooney 201., Turbo Mooney 231/M20K
1P/S	M200	Rockwell Int'l Corp. Commander 200
1P/S	M22	Mooney Aircraft Corp. Mark 22, Mustang
2P/L	M404	Martin Co. Martin 404
1P/S	M5	Maule Aircraft Corp. M-5 180C/200/235C Lunar-Rocket, 210TC Strata-Rocket, Patroller
1P/S	M6	Maule Aircraft Corp. M-6 Super Rocket
1P/S	M7	Maule Aircraft Corp. M-7-235, MT-7, MX-7-160/180/235, MXT-7-160/180 Super Rocket, Star Rocket
1T/S	M7T	Maule Aircraft Corp. MX-7-160/180/235, MXT-7-420 Star Craft[1]
3J/H	MD11	McDonnell Douglas Corp. MD-11
2J/L	MD80	McDonnell Douglas Corp. MD-80 Series
2J/L	MD90	McDonnell Douglas Corp. MD-90
2J/L	MRC	Panavia Tornado ADV[6]
2T/S	MU2	Mitsubishi Aircraft Int'l Inc. Mitsubishi MU-2., MU-2B-60 Marquise, MU-2B-40 Solitaire[1]
2J/S+	MU30	Beech Aircraft Co. Beechjet 400/T-1 Jayhawk/MU300 Diamond

2J/S+	MU30	Mitsubishi Aircraft Int'l Inc. I/MU-300., Mitsubishi Diamond I/MU-300
2T/S+	N262	Nord Aviation Mohawk 298, Fregate
2P/S	P136	Piaggio P136 Gull
2P/S	P180	Piaggio P180 Avanti[2]
2T/S	P31T	Piper Aircraft Corp. Cheyenne 1/2,
1P/S	P31T	Piper Aircraft Corp. T-1040
2P/S	P337	Cessna Aircraft Co. Pressurized Skymaster T337G, P337
2P/S	P68	Partenavia Construzioni Aeronautiche P68/B/C/-TC, Victor, Observer/P68R
1P/S	PA18	Piper Aircraft Corp. Super Cub
1P/S	PA20	Piper Aircraft Corp. Pacer
1P/S	PA22	Piper Aircraft Corp. Tri-Pacer, Colt, Caribbean
2P/S	PA23	Piper Aircraft Corp. Apache 150/160
1P/S	PA24	Piper Aircraft Corp. Comanche
2P/S	PA27	Piper Aircraft Corp. Aztec. Turbo Aztec
1P/S	PA28	Piper Aircraft Corp. Cherokee, Archer, Dakota, Turbo Dakota, Warrior, Cadet, Cruiser, Pathfinder
1P/S	PA28R	Piper Aircraft Corp. Cherokee Arrow[1]
1P/S	PA28T	Piper Aircraft Corp. Cherokee Arrow 4, Turbo Arrow 4
2P/S	PA30	Piper Aircraft Corp. Twin Comanche, Turbo twin Comanche., Twin Commanche PA-39TC[4]
2P/S	PA31	Piper Aircraft Corp. Chieftan, Mohave, Navajo, T-1020
1P/S	PA32	Piper Aircraft Corp. Cherokee Six, Lance, (Turbo) Saratoga
2P/S	PA34	Piper Aircraft Corp. Seneca 2/3
1P/S	PA36	Piper Aircraft Corp. Brave, Pawnee Brave, Super Brave
1P/S	PA38	Piper Aircraft Corp. Tomahawk
2T/S	PA42	Piper Aircraft Corp. Cheyenne 3/400
2P/S	PA44	Piper Aircraft Corp. Seminole, Turbo Seminole
1P/S	PA46	Piper Aircraft Corp. Malibu, Malibu Mirage
1T/S	PC12	Pilatus Flugzeugwerke AG PC-12
1T/S	PC6T	Pilatus Flugzeugwerke AG PC-6A/B/C Turbo Porter
1T/S	PC7	Pilatus Flugzeugwerke AG PC-7 Turbo Trainer
1P/S	R44	Robinson Helicopter Inc., R44 Astro[2]
1P/S	RANG	Navion Rangemaster Aircraft Corp. Rangemaster
2J/L	S3	Lockheed Martin Corp. Viking S-3/3B
1T/S	S360	Aerospatiale Dauphine SA-360/361
2J/S+	S601	Aerospatiale Corvette SN601
2T/L	S61	Sikorsky Aircraft Corp., SH-3H Sea King[2],S-61A/B/D/L/N Sea King, Commando, CH-124
2T/S	S65C	Aerospatiale Dauphine 2 SA-365C
2T/S	S76	Sikorsky Aircraft Model S-76, Spirit, Eagle
2J/S+	SBR1	Rockwell Int'l Corp. Sabreliner 65/40/50/60
2T/S	SC7	Short Brothers LTD. Shorts SC7 Skyvan, Skyliner
2T/L	SF34	SAAB & Fairchild Ind. SF-340
2T/S+	SH33	Short Brothers LTD. Shorts 330, Sherpa C-23A [3]
2T/S+	SH36	Short Brothers LTD. Shorts 360
1J/L	SSAB	Rockwell Int'l Corp. Super Sabre F-100
1P/S	ST75	Boeing Co. Stearman
2T/S+	STAR	Beech Aircraft Co. Starship 2000
2T/S	SW2	Fairchild Ind. (Swearingen) Merlin 2
2T/S+	SW3	Fairchild Ind. (Swearingen) Merlin 3
2T/S	SW4	Fairchild Ind. (Swearingen) Metro, Merlin 4
2J/L	T2	Rockwell Int'l Corp. T-2C Buckeye
1P/S	T28	Rockwell Int'l Corp. Trojan, Nomair, Nomad
2J/L	T33	Lockheed Corp. T-33, T-Bird

1P/S	T34P	Beech Aircraft Co. Mentor T34 A/B, E-17
1T/S	T34T	Beech Aircraft Co., Turbo Mentor T-34C[1]
2J/S	T37	Cessna Aircraft Co. Cessna 318
2J/S+	T38	Northrop Corp. T-38 Talon
1P/S	TAMP	Aerospatiale Tampico TB-9
1P/S	TAMP	Aerospatiale Tampico TB-9
1T/S	TBM7	Aerospatiale TBM TB-700
1P/S	TOBA	Aerospatiale Tabago TB10C/200
1P/S	TRIN	Aerospatiale Trinidad TB-20
3P/S	TRIS	Britten Norman LTD. BN-2A Mark III Islander
3J/L	TU54	Tupolev TU-154, 154A/B/B2/C/M[6]
1J/S+	U2	Lockheed Corp. U-2, ER-2 NASA Earth Survey[3]
2T/S	U21	Beech Aircraft Co. Ute
1T/S	UH1	Bell Helicopter Textron Huey/Iroquois/Model 205 A-1
2T/S	V1	Grumman Aerospace Corp. Mohawk
2T/S	V10	Rockwell Int'l Corp. Bronco
4J/H	VC10	Britten Norman LTD. VC-10
2J/S+	WW23	Israel Aircraft Ind. 1123 Westwind
2J/S+	WW24	Israel Aircraft Ind. 1124 Westwind., 1124A Westwind 2
3J/S+	YK40	Yakovlev Yak-40 Codling[3]
3J/L	YK42	Yakovlev Yak-42 Clobber[3]
2T/L	YS11	Nihon Kokuki Kabushiki Kaisha & National Aeroplane Manufacturing Co. YS-11
J/L	*	jet (400 kts and above), large, 32,000’ and above
J/S+	*	jet (400 kts and above), small+, 0 – 31,900’ altitude
T/L	*	turboprop (279 – 399 kts), large, 35,000’ and above
T/S+	*	turboprop (279 – 399 kts), small+, 25,100’ – 34,900’ altitude
T/S	*	turboprop (279 – 399 kts), small, 0 – 25,000’ altitude
P/S+	*	piston (0 –279 kts), small+, 20,100’ altitude and above
P/S	*	piston (0 – 279 kts), small, 0 – 20,000’ altitude

* Where the a/c type designator is unknown, the aircraft class (a/c size and engine type) is estimated based the maximum observed true airspeed and the maximum observed altitude as defined in the table.

Number of Engines	Engine Type	Size Type
1, 2, 3, or 4	J = jet	H = heavy
	T = turboprop	LH = large-to-heavy
	P = piston	L = large
		LS = large-to-small
		S+ = small-to-large
		S = small

FAA Aircraft Weight Classes

Heavy: over 255,000 lbs takeoff weight capability
Large: 41,000 -255,000 lbs maximum certified takeoff weight
Small+: 12,500-41,000 lbs maximum certified takeoff weight
Small: under 12,500 lbs maximum certified takeoff weight

Sources
1. Aircraft/, Information, Appendices A & B, FAA Handbook 7110.65L effective 8/13/98.
2. Aviation Week & Space Technology-Aerospace Source Book, January 19,1998.
3. Jane’s Aircraft Recognition Guides, 1996, 1982.
4. Jane’s Encyclopedia of Aviation, 1996.
5. Census U.S. Civil Aircraft, Federal Aviation Administration, Cy1993 (last time published).
6. Base of Aircraft Data (BADA) Synonym File, September 9, 1997.

Otherwise Source 1 above applies.

Appendix B -- Aircraft Operating Cost Rates

Engine Type	Engine No.	A/C Size	1996 Operating Cost Rate[1] ($/hour) Crew	Maint	Subtotal	Fuel&Oil Airborne	Fuel&Oil Ground[2]	Source[1]
J	4	H	2488	1699	4187	2703	901	Table 4-1B
J	4	L	582	990	1572	829	276	Table 4-1B
J	3	H	1981	1459	3440	1827	609	Table 4-1B
J	3	L	1188	712	1900	1025	342	Table 4-1B
J	3	S+	280	596	876	626	209	Table 4-20
J	2	H	1489	780	2269	1152	384	Table 4-1B
J	2	LH	1164	493	1657	754	251	Table 4-12
J	2	L	851	531	1382	651	217	Table 4-12
J	2	LS	551	523	1074	535	178	Interpolate
J	2	S+	251	515	766	420	140	Table 4-20
J	2	S	225	361	586	249	83	Table 4-20
T	4	L	672	998	1670	571	190	Table 4-14
T	2	L	205	344	549	270	90	Table 4-6
T	2	S+	201	303	504	181	60	Table 4-6
T	2	S	193	257	450	147	49	Table 4-6
T	1	S+	117	140	257	109	36	Table 4-6
T	1	S	114	110	224	103	34	Table 4-6
P	4	L	250	275	525	500	167	Extrapolate
P	2	L	190	215	405	390	130	Table 4-18
P	2	S+	200	204	404	193	64	Tbls 4-3B,6,18
P	2	S	72	93	165	68	23	Table 4-6
P	1	S+	72	60	132	45	15	Interplolate
P	1	S	72	27	99	22	7	Table 4-6
SST[3](Rockwell B1B)			2488	1699	4187	7363	2454	Tbls 4-1B,21

Consumer Price Index (CPI)[4]		Oil&Gas Deflator[4]	
1982-84 base	100.0	1992 base	100.0
1996	153.0	1996	104.2
1996	153.0	1996	104.2

Escalation factor	Crew	Maint	Subtotal	Fuel&Oil Airborne	Fuel&Oil Ground
1996	1.000	1.000	1.000	1.000	1.000

1. Source: Federal Aviation Administration, "Economic Values for Evaluation of Federal Administration Investment and Regulatory Programs," Final Report FAA-APO-98-8, Office of Aviation Policy and Plans, Washington, DC 20591 (June 1998
2. Ground fuel and oil cost is assumed to be 1/3 of ariborne
3. SST crew and maintenance costs are assumed to be same as 4J/H
4. Source: Federal Aviation Administration, "FAA Aviation Forecasts Fiscal Years 1998-2009," Final Report FAA-APO-98-1, Office of Aviation Policy and Plans, Washington, DC 20591 (March 1998),

Hourly Aircraft Operating Cost Rates

Engine Type	Engine No.	A/C Size	Crew	Maint	Subtotal	Fuel&Oil Airborne	Fuel&Oil Ground
			1996 Operating Cost Rate ($/hour)				
J	4	H	2488.00	1699.00	4187.00	2703.00	901.00
J	4	L	582.00	990.00	1572.00	829.00	276.33
J	3	H	1981.00	1459.00	3440.00	1827.00	609.00
J	3	L	1188.00	712.00	1900.00	1025.00	341.67
J	3	S+	280.00	596.00	876.00	626.00	208.67
J	2	H	1489.00	780.00	2269.00	1152.00	384.00
J	2	LH	1164.00	493.00	1657.00	754.00	251.33
J	2	L	851.00	531.00	1382.00	651.00	217.00
J	2	LS	551.00	523.00	1074.00	535.00	178.33
J	2	S+	251.00	515.00	766.00	420.00	140.00
J	2	S	225.00	361.00	586.00	249.00	83.00
T	4	L	672.00	998.00	1670.00	571.00	190.33
T	2	L	205.00	344.00	549.00	270.00	90.00
T	2	S+	201.00	303.00	504.00	181.00	60.33
T	2	S	193.00	257.00	450.00	147.00	49.00
T	1	S+	117.00	140.00	257.00	109.00	36.33
T	1	S	114.00	110.00	224.00	103.00	34.33
P	4	L	250.00	275.00	525.00	500.00	166.67
P	2	L	190.00	215.00	405.00	390.00	130.00
P	2	S+	200.00	204.00	404.00	193.00	64.33
P	2	S	72.00	93.00	165.00	68.00	22.67
P	1	S+	72.00	60.00	132.00	45.00	15.00
P	1	S	72.00	27.00	99.00	22.00	7.33
SST (Rockwell B1B)			2488.00	1699.00	4187.00	7363.00	2454.33

Appendix C -- Runway System Modeling Data

Current System and TMA

THRESHOLD EXCESS SPACING BUFFER (secs)

Same Runway

VFR: ARR1-ARR2	SML	LRG	757	HVY
SML	25.7	25.1	25.1	24.6
LRG	27.8	25.2	25.2	24.5
757	28.9	26.4	26.4	25.7
HVY	30.5	28.2	28.2	25.7

IFR: ARR1-ARR2	SML	LRG	757	HVY
SML	25.7	25.1	25.1	24.6
LRG	27.8	25.2	25.2	24.5
757	28.9	26.4	26.4	25.7
HVY	30.5	28.2	28.2	25.7

VFR: ARR1-DEP2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: ARR1-DEP2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-ARR2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-ARR2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-DEP2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-DEP2	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

Interacting Runways

VFR: ARR1-ARR2	SML	LRG	757	HVY
SML	25.7	25.1	25.1	24.6
LRG	27.8	25.2	25.2	24.5
757	28.9	26.4	26.4	25.7
HVY	30.5	28.2	28.2	25.7

IFR: ARR1-ARR2	SML	LRG	757	HVY
SML	25.7	25.1	25.1	24.6
LRG	27.8	25.2	25.2	24.5
757	28.9	26.4	26.4	25.7
HVY	30.5	28.2	28.2	25.7

VFR: ARR1-DEP2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: ARR1-DEP2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-ARR2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-ARR2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-DEP2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-DEP2	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

THRESHOLD EXCESS SPACING BUFFER (secs)

Same Runway

VFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	23.65	23.29	23.29	23.03
LRG	24.99	23.24	23.24	22.8
757	25.62	23.99	23.99	23.31
HVY	26.56	25.1	25.1	23.31

IFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	23.65	23.29	23.29	23.03
LRG	24.99	23.24	23.24	22.8
757	25.62	23.99	23.99	23.31
HVY	26.56	25.1	25.1	23.31

VFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

Interacting Runways

VFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	23.65	23.29	23.29	23.03
LRG	24.99	23.24	23.24	22.8
757	25.62	23.99	23.99	23.31
HVY	26.56	25.1	25.1	23.31

IFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	23.65	23.29	23.29	23.03
LRG	24.99	23.24	23.24	22.8
757	25.62	23.99	23.99	23.31
HVY	26.56	25.1	25.1	23.31

VFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

THRESHOLD EXCESS SPACING BUFFER (secs)

Same Runway

VFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	22.64	22.28	22.28	22.01
LRG	24.01	22.22	22.22	21.77
757	24.66	22.98	22.98	22.28
HVY	25.63	24.12	24.12	22.28

IFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	22.64	22.28	22.28	22.01
LRG	24.01	22.22	22.22	21.77
757	24.66	22.98	22.98	22.28
HVY	25.63	24.12	24.12	22.28

VFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

VFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

IFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.6	2.6	2.6	2.6
LRG	2.6	2.6	2.6	2.6
757	2.6	2.6	2.6	2.6
HVY	2.6	2.6	2.6	2.6

Interacting Runways

VFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	22.64	22.28	22.28	22.01
LRG	24.01	22.22	22.22	21.77
757	24.66	22.98	22.98	22.28
HVY	25.63	24.12	24.12	22.28

IFR: ARR1-ARR2

	SML	LRG	757	HVY
SML	22.64	22.28	22.28	22.01
LRG	24.01	22.22	22.22	21.77
757	24.66	22.98	22.98	22.28
HVY	25.63	24.12	24.12	22.28

VFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: ARR1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-ARR2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

VFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

IFR: DEP1-DEP2

	SML	LRG	757	HVY
SML	2.4	2.4	2.4	2.4
LRG	2.4	2.4	2.4	2.4
757	2.4	2.4	2.4	2.4
HVY	2.4	2.4	2.4	2.4

Modeled Runway Use Configurations

Airport	Wx.	Arrival Runways	Departure Runways
DEN	IFR	34, 35L, 35R	25, 34
	VFR	34, 35L, 35R	8, 25, 34
DFW	IFR	13R, 17C, 18R	13L, 17R ,18L
	VFR	17L, 17C, 18R, 13R	13L, 17R, 18L
EWR	IFR	04R	04L
	VFR	04R, 11	04L, 11
JFK	IFR	13L, 13R	13L, 13R
	VFR	13L, 13R	13L, 13R
LAX	IFR	25L, 24R	25R, 24L
	VFR	25L, 24R	25R, 24L
LGA	IFR	04	13
	VFR	22	13
MSP	IFR	29L, 29R	29L, 29R
	VFR	29L, 29R	29L, 29R
ORD	IFR	14L, 14R	09L, 09R
	VFR	14R, 22R, 22L	27L, 22L
PHL	IFR	27R, 17	27L, 17
	VFR	27R, 17	27L, 17
SFO	IFR	28R	28R, 28L
	VFR	28R, 28L	01L, 01R

Appendix D -- Modeled Arrival and Departure Procedures

Runway Assignment by Arrival and Departure Fix

	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
1	DEN	IFR	RAMMS TOMSN	34 34	ADANE SOLAR BAYLR CONNR ZIMMR	25 25 25 25 25
			POWDR LARKS QUAIL DANDD	35L 35L 35L 35L	YAMMI YALES YOKES EEONS EMMYS EXTAN EPKEE	34 34 34 34 34 34 34
			SAYGE LANDR	35R 35R		
		VFR	RAMMS TOMSN	34 34	EEONS EMMYS EXTAN EPKEE	8 8 8 8
			POWDR LARKS QUAIL DANDD	35L 35L 35L 35L	ADANE SOLAR BAYLR CONNR ZIMMR	25 25 25 25 25
			SAYGE LANDR	35R 35R	YAMMI YALES YOKES	34 34 34

	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
2	DFW	IFR	BAMBE GREGS	13R 13R	NOBLY TRISS SOLDO CLARE	13L 13L 13L 13L
			SASIE KARLA	17C 17C	FERRA SLOTT CEOLA PODDE NELYN JASPA ARDIA DARTZ	17R 17R 17R 17R 17R 17R 17R 17R
			FLIPP TACKE DODJE KNEAD FEVER	18R 18R 18R 18R 18R	LOWGN BLECO GRABE AKUNA	18L 18L 18L 18L
		VFR	BAMBE GREGS	13R 13R	NOBLY TRISS SOLDO CLARE	13L 13L 13L 13L
			SASIE KARLA	17C 17C	FERRA SLOTT CEOLA PODDE NELYN JASPA ARDIA DARTZ	17R 17R 17R 17R 17R 17R 17R 17R
			TACKE	17L	LOWGN BLECO GRABE	18L 18L 18L

					AKUNA	18L
			FLIPP DODJE KNEAD FEVER	18R 18R		
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
3	EWR	IFR	ROBBINSVILLE METRO SWEET SPARTA	04R 04R 04R 04R	COLTS NECK SOLBERG BROADWAY COATE NEION HAAYS GAYEL CARMEL	04L 04L 04L 04L 04L 04L 04L 04L
		VFR	ROBBINSVILLE METRO	04R 04R	COLTS NECK SOLBERG BROADWAY	04L 04L 04L
			SWEET SPARTA	11 11	COATE NEION HAAYS GAYEL CARMEL	11 11 11 11 11
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
4	JFK	IFR	ROBER DEER PARK	13L 13L	WAVEY SHIPP HAPIE BETTE BRIDGEPORT CARMEL BREZY SPARTA	13L 13L
			LENDY CAMRN	13R 13R	BROADWAY SOLBERG ROBBINSVILLE DIXIE	13R 13R
		VFR	ROBER DEER PARK	13L 13L	WAVEY SHIPP HAPIE BETTE BRIDGEPORT CARMEL BREZY SPARTA	13L 13L
			LENDY CAMRN	13R 13R	BROADWAY SOLBERG ROBBINSVILLE DIXIE	13R 13R
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
5	LAX	IFR	BAYER ARNES	25L 25L	SEAL BEACH OCEANSIDE SANTA CATALINA PERCH	25R 25R 25R 25R
			BOGET SAUGS SYMON	24R 24R 24R	VENTURA GORMAN COOPP	24L 24L 24L
		VFR	BAYER ARNES	25L 25L	SEAL BEACH OCEANSIDE SANTA CATALINA PERCH	25R 25R 25R 25R
			BOGET SAUGS SYMON	24R 24R 24R	VENTURA GORMAN COOPP	24L 24L 24L
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
6	LGA	IFR	NOBBI BAYSE BEUTY	04 04 04	SPARTA BROADWAY SOLBERG	13 13 13

			SOMTO	04	ROBBINSVILLE	13
					DIXIE	13
					WAVEY	13
					SHIPP	13
					BRIDGEPORT	13
					MERIT	13
					GREKI	13
		VFR	NOBBI	22	SPARTA	13
			BAYSE	22	BROADWAY	13
			BEUTY	22	SOLBERG	13
			SOMTO	22	ROBBINSVILLE	13
					DIXIE	13
					WAVEY	13
					SHIPP	13
					BRIDGEPORT	13
					MERIT	13
					GREKI	13
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
7	MSP	IFR	SEANE	29L	PRAGS	29L
			SHPRD	29L	PRESS	29L
			TWINZ	29R	SNINE	29R
			OLLEE	29R	FUDGE	29R
		VFR	SEANE	29L	PRAGS	29L
			SHPRD	29L	PRESS	29L
			TWINZ	29R	SNINE	29R
			OLLEE	29R	FUDGE	29R
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
8	ORD	IFR	BEARZ	14L	PETTY	09L
			PIVOT	14L	MUSKY	09L
			TEDDY	14R	PEOTONE	09R
			BENKY	14R	NEWTT	09R
					HINCK	09R
					SIMMN	09R
		VFR	TEDDY	14R	HINCK	27L
			BENKY	14R	SIMMN	27L
					PETTY	27L
			PIVOT	22R	MUSKY	22L
					PEOTONE	22L
					NEWTT	22L
			BEARZ	22L		
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
9	PHL	IFR	TERRI	27R	MODENA	27L
			CEDAR LAKE	27R	POTTSTOWN	27L
					ALLENTOWN	27L
					YARDLEY	27L
					ROBBINSVILLE	27L
			SPUDS	17	COYLE	17
			BUCKS	17	CEDAR LAKE	17
					WOODSTOWN	17
					DUPONT	17
		VFR	TERRI	27R	MODENA	27L
			CEDAR LAKE	27R	POTTSTOWN	27L
					ALLENTOWN	27L
					YARDLEY	27L
					ROBBINSVILLE	27L
			SPUDS	17	COYLE	17
			BUCKS	17	CEDAR LAKE	17
					WOODSTOWN	17
					DUPONT	17
	Airport	Proc	Arrival Fix	Arrival Runway	Departure Fix	Departure Rwy
10	SFO	IFR	LOZIT	28R	REBAS	28R
			LOCKE	28R	SACRAMENTO	28R
			CEDES	28R	LINDEN	28R
			BOLDR	28R	MANTECA	28R
			EUGEN	28R		
			PIRAT	28R		

				STINS	28R		
						WAGES	28L
						SEGUL	28L
						STINS	28L
			VFR	LOZIT	28R	WAGES	01L
				LOCKE	28R	SEGUL	01L
				CEDES	28R	STINS	01L
				BOLDR	28L	REBAS	01R
				EUGEN	28L	SACRAMENTO	01R
				PIRAT	28L	LINDEN	01R
				STINS	28L	MANTECA	01R

Appendix E -- DFW Traffic and Delay Summary

DFW - Dallas Ft. Worth: 1996 Number of Schedule Operations per Hour at Runway

Hourly Scheduled Aircraft Operations Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	Total
Departure	0	2	13	11	2	8	14	40	69	70	65	87	43	108	73	66	70	75	43	98	97	22	41	15	1132
Arrival	0	0	0	2	7	16	35	17	55	76	33	91	40	69	107	55	48	91	77	89	64	39	11	10	1032
Total	0	2	13	13	9	24	49	57	124	146	98	178	83	177	180	121	118	166	120	187	161	61	52	25	2164

DFW - Dallas Ft. Worth: 1996 Hourly Traffic and Average Aircraft Delay, VFR Day at Runway

Hourly Throughput Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	All
Current																									
Departure	0	2	13	11	2	8	14	39	70	70	64	88	42	109	73	64	72	75	42	99	97	22	38	18	1132
Arrival	0	0	0	2	7	13	37	18	53	75	34	80	52	68	102	53	57	84	79	93	65	39	11	10	1032
Total	0	2	13	13	9	21	51	57	123	145	98	168	94	177	175	117	129	159	121	192	162	61	49	28	2164
TMA																									
Departure	0	2	13	11	2	8	14	39	70	70	64	88	42	109	73	64	72	75	42	99	97	22	38	18	1132
Arrival	0	0	0	2	7	14	37	17	54	75	34	80	51	69	104	53	54	87	78	92	64	39	11	10	1032
Total	0	2	13	13	9	22	51	56	124	145	98	168	93	178	177	117	126	162	120	191	161	61	49	28	2164
PFAST																									
Departure	0	2	13	11	2	8	14	39	70	70	64	88	42	109	73	63	73	75	42	99	97	22	38	18	1132
Arrival	0	0	0	2	7	13	37	18	53	75	34	80	52	68	103	52	57	85	78	93	65	39	11	10	1032
Total	0	2	13	13	9	21	51	57	123	145	98	168	94	177	176	115	130	160	120	192	162	61	49	28	2164
AFAST																									
Departure	0	2	13	11	2	8	14	39	70	70	64	88	42	109	73	63	73	75	42	99	97	22	38	18	1132
Arrival	0	0	0	2	7	13	37	18	53	75	34	80	52	68	103	52	57	85	78	93	65	39	11	10	1032
Total	0	2	13	13	9	21	51	57	123	145	98	168	94	177	176	115	130	160	120	192	162	61	49	28	2164
EDP																									
Departure	0	2	13	11	2	8	14	39	70	70	64	88	42	109	73	63	73	75	42	99	97	22	38	18	1132
Arrival	0	0	0	2	7	14	37	17	54	75	34	80	51	69	105	52	54	87	78	92	64	39	11	10	1032
Total	0	2	13	13	9	22	51	56	124	145	98	168	93	178	178	115	127	162	120	191	161	61	49	28	2164

Hourly Average Aircraft Delay (minutes/operation) Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	All
Current																									
Departure	0.00	0.00	0.08	0.08	0.00	0.24	0.05	0.16	0.27	0.62	0.25	0.43	0.28	0.60	0.44	0.27	0.32	0.33	0.24	0.85	1.35	0.10	0.27	0.54	0.48
Arrival	0.00	0.00	0.00	1.74	2.08	1.27	1.58	1.22	2.73	2.83	2.34	3.84	4.36	3.64	5.77	2.65	2.90	3.56	2.28	2.47	2.23	1.62	1.59	0.97	3.07
Average	0.00	0.00	0.08	0.33	1.62	0.88	1.16	0.49	1.33	1.76	0.97	2.05	2.54	1.77	3.55	1.35	1.46	2.03	1.57	1.63	1.70	1.07	0.57	0.69	1.72
TMA																									
Departure	0.00	0.00	0.08	0.08	0.00	0.24	0.05	0.16	0.27	0.62	0.25	0.45	0.30	0.64	0.44	0.27	0.38	0.33	0.24	0.78	1.20	0.10	0.25	0.54	0.47
Arrival	0.00	0.00	0.00	0.87	1.06	0.65	1.00	0.66	1.78	1.86	1.38	2.84	3.40	2.64	4.83	1.68	1.89	2.39	1.41	1.51	1.42	0.91	0.88	0.51	2.15
Average	0.00	0.00	0.08	0.20	0.83	0.50	0.74	0.31	0.93	1.26	0.64	1.59	2.00	1.41	3.02	0.91	1.03	1.44	1.00	1.13	1.29	0.62	0.39	0.53	1.28
PFAST																									
Departure	0.00	0.00	0.08	0.08	0.00	0.24	0.05	0.16	0.27	0.60	0.25	0.43	0.27	0.63	0.44	0.28	0.32	0.32	0.24	0.85	1.34	0.10	0.27	0.54	0.48
Arrival	0.00	0.00	0.00	1.74	2.07	1.27	1.57	1.21	2.73	2.72	2.29	3.72	4.33	3.57	5.64	2.34	2.87	3.47	2.25	2.46	2.29	1.59	1.57	0.97	3.01
Average	0.00	0.00	0.08	0.33	1.61	0.88	1.15	0.49	1.33	1.70	0.96	2.00	2.52	1.76	3.48	1.21	1.44	1.99	1.55	1.63	1.72	1.05	0.56	0.69	1.69
AFAST																									
Departure	0.00	0.00	0.08	0.08	0.00	0.24	0.05	0.16	0.27	0.61	0.25	0.43	0.29	0.63	0.48	0.27	0.32	0.33	0.24	0.84	1.33	0.10	0.28	0.54	0.49
Arrival	0.00	0.00	0.00	1.74	2.06	1.27	1.59	1.20	2.75	2.75	2.31	3.70	4.26	3.37	5.55	2.35	2.88	3.46	2.25	2.42	2.29	1.58	1.57	0.97	2.99
Average	0.00	0.00	0.08	0.33	1.61	0.87	1.17	0.49	1.34	1.72	0.96	1.99	2.49	1.68	3.45	1.21	1.44	1.99	1.55	1.61	1.72	1.05	0.57	0.69	1.68
EDP																									
Departure	0.00	0.00	0.08	0.08	0.00	0.24	0.05	0.16	0.27	0.61	0.25	0.45	0.29	0.64	0.52	0.25	0.32	0.33	0.24	0.80	1.23	0.10	0.25	0.54	0.48
Arrival	0.00	0.00	0.00	0.87	1.05	0.65	1.01	0.64	1.74	1.79	1.34	2.74	3.31	2.43	4.74	1.48	1.89	2.28	1.43	1.48	1.50	0.89	0.74	0.51	2.10
Average	0.00	0.00	0.08	0.20	0.81	0.50	0.75	0.31	0.91	1.22	0.63	1.54	1.94	1.33	3.01	0.81	0.99	1.38	1.02	1.13	1.33	0.61	0.36	0.53	1.25

DFW - Dallas Ft. Worth: 2015 Number of Schedule Operations per Hour at Runway

Hourly Scheduled Aircraft Operations Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	Total
Departure	8	13	20	31	4	10	15	56	112	112	138	171	88	160	125	143	127	107	61	135	110	35	38	23	1842
Arrival	18	6	4	6	14	34	46	35	86	121	55	140	86	92	159	97	79	124	130	141	108	56	16	0.99	1674
Total	26	19	24	37	18	44	61	91	198	233	193	311	174	252	284	240	206	231	191	276	218	91	54	44	3516

DFW - Dallas Ft. Worth: 2015 Hourly Traffic and Average Aircraft Delay, VFR Day at Runway

Hourly Throughput Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	All
Current																									
Departure	7	14	20	31	4	10	14	57	112	89	161	162	96	160	100	166	130	103	64	136	97	48	32	29	1842
Arrival	17	7	4	6	14	32	46	34	81	114	68	98	120	101	123	120	92	107	134	154	98	65	17	0.99	1673
Total	24	21	24	37	18	42	60	91	193	203	229	260	216	261	223	286	222	210	198	290	195	113	49	50	3515
TMA																									
Departure	7	14	20	31	4	10	14	57	112	89	161	162	96	160	102	164	130	103	64	136	97	48	32	29	1842
Arrival	18	6	4	6	14	32	48	34	79	116	68	98	122	96	128	120	88	111	131	154	101	61	17	22	1674
Total	25	20	24	37	18	42	62	91	191	205	229	260	218	256	230	284	218	214	195	290	198	109	49	51	3516
PFAST																									
Departure	7	14	20	31	4	10	14	57	112	89	161	166	92	160	106	160	130	103	64	136	97	48	32	29	1842
Arrival	17	7	4	6	14	32	46	34	81	117	65	101	120	99	122	124	88	109	133	152	95	69	18	20	1673
Total	24	21	24	37	18	42	60	91	193	206	226	267	212	259	228	284	218	212	197	288	192	117	50	49	3515
AFAST																									
Departure	7	14	20	31	4	10	14	57	112	89	161	166	92	160	106	160	130	103	64	136	97	48	32	29	1842
Arrival	17	7	4	6	14	32	46	34	81	118	64	101	120	99	123	123	88	109	133	152	97	67	18	20	1673
Total	24	21	24	37	18	42	60	91	193	207	225	267	212	259	229	283	218	212	197	288	194	115	50	49	3515
EDP																									
Departure	7	14	20	31	4	10	14	57	112	89	161	166	93	159	106	158	132	103	64	136	97	48	32	29	1842
Arrival	18	6	4	6	14	32	48	33	80	122	62	103	119	94	130	120	86	110	132	153	96	67	18	21	1674
Total	25	20	24	37	18	42	62	90	192	211	223	269	212	253	236	278	218	213	196	289	193	115	50	50	3516

Hourly Average Aircraft Delay (minutes/operation) Starting at Indicated Time (Local Time)

Ops Type	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	All
Current																									
Departure	-0.01	0.06	0.25	0.23	0.00	0.21	0.12	0.26	2.03	1.94	6.70	7.93	1.94	5.66	2.53	4.09	1.42	0.61	0.58	2.54	2.80	2.03	0.29	0.98	3.18
Arrival	1.89	1.55	1.58	1.78	2.11	1.97	3.40	1.98	4.08	4.99	4.81	5.76	14.25	8.56	9.44	9.05	4.38	7.56	5.93	8.82	9.45	3.24	1.23	0.99	6.90
Average	1.33	0.55	0.47	0.48	1.64	1.55	2.63	0.90	2.89	3.66	6.14	7.11	8.78	6.78	6.34	6.17	2.65	4.15	4.20	5.87	6.14	2.72	0.62	1.33	4.95
TMA																									
Departure	-0.01	0.06	0.25	0.23	0.00	0.21	0.12	0.26	2.07	1.94	6.70	7.82	1.80	5.64	2.72	3.71	1.40	0.61	0.58	2.54	2.80	2.06	0.29	0.98	3.14
Arrival	1.04	0.77	0.79	1.15	1.27	1.33	2.34	1.24	3.06	4.38	3.78	4.94	12.81	7.70	8.09	7.56	3.15	6.73	4.57	7.54	8.31	1.87	0.64	1.14	5.83
Average	0.75	0.27	0.34	0.38	0.98	1.06	1.84	0.63	2.48	3.32	5.83	6.74	7.96	6.41	5.70	5.33	2.11	3.79	3.26	5.19	5.61	1.95	0.41	1.05	4.42
PFAST																									
Departure	-0.01	0.06	0.25	0.23	0.00	0.21	0.12	0.26	1.94	1.94	7.40	7.49	1.24	5.64	2.70	3.00	1.34	1.45	0.58	2.56	2.80	2.00	0.29	0.98	3.12
Arrival	1.88	1.55	1.58	1.78	2.11	1.97	3.37	1.97	4.03	5.00	4.33	5.80	12.81	8.20	9.94	8.78	4.14	7.36	5.77	8.75	10.45	3.57	1.39	1.35	6.79
Total	1.33	0.55	0.47	0.48	1.64	1.55	2.62	0.90	2.82	3.68	6.52	6.85	7.79	6.62	6.57	5.52	2.47	4.49	4.09	5.83	6.59	2.93	0.69	1.13	4.87
AFAST																									
Departure	-0.01	0.06	0.25	0.23	0.00	0.21	0.12	0.26	1.94	1.94	7.48	7.49	1.24	5.64	2.71	3.09	1.50	1.40	0.58	2.59	2.80	2.00	0.29	0.98	3.15
Arrival	1.88	1.54	1.58	1.78	2.10	1.96	3.36	1.97	4.01	4.76	4.39	5.58	12.82	8.09	9.77	9.03	4.06	7.58	6.02	8.68	10.06	3.22	1.40	1.39	6.76
Total	1.33	0.55	0.47	0.48	1.64	1.54	2.61	0.90	2.81	3.55	6.60	6.76	7.79	6.58	6.50	5.67	2.53	4.58	4.26	5.80	6.43	2.71	0.69	1.14	4.87
EDP																									
Departure	-0.01	0.06	0.25	0.23	0.00	0.21	0.12	0.26	1.94	1.94	6.74	7.41	1.23	5.66	2.71	3.12	1.54	1.44	0.58	2.59	2.80	2.00	0.29	0.98	3.08
Arrival	1.04	0.77	0.79	1.15	1.25	1.31	2.32	1.27	2.94	4.00	2.83	5.03	10.49	6.79	7.67	7.35	2.88	6.46	4.79	6.80	9.86	2.77	0.69	0.92	5.51
Average	0.74	0.27	0.34	0.38	0.97	1.05	1.82	0.63	2.36	3.13	5.65	6.50	6.43	6.08	5.44	4.94	2.07	4.03	3.42	4.82	6.31	2.45	0.43	0.95	4.24

Appendix F -- IMC Persistence by Airport

CAT I IFR Duration (hours)	IFR Duration Distribution* by Airport (percent)										
	ATL	BOS	DFW	DEN	DTW	EWR	JFK	LAX	LGA	ORD	SFO
1	25%	28%	39%	29%	32%	29%	27%	23%	24%	30%	33%
2	15%	17%	16%	18%	16%	17%	16%	16%	13%	14%	19%
3	11%	9%	11%	13%	12%	10%	9%	13%	9%	11%	11%
4	8%	7%	6%	8%	8%	7%	6%	10%	9%	9%	8%
5	7%	4%	5%	6%	6%	5%	5%	8%	6%	6%	6%
6	5%	4%	4%	5%	5%	4%	5%	5%	4%	4%	4%
7	4%	4%	2%	4%	4%	4%	3%	6%	3%	3%	3%
8	4%	4%	3%	2%	3%	3%	3%	3%	5%	2%	3%
9	3%	2%	2%	1%	2%	2%	4%	4%	3%	2%	3%
10	3%	2%	2%	1%	2%	3%	4%	2%	3%	3%	2%
11	2%	2%	1%	2%	2%	3%	2%	1%	4%	2%	1%
12	1%	2%	1%	2%	1%	2%	2%	2%	2%	1%	1%
13	2%	2%	1%	1%	1%	1%	2%	2%	2%	1%	1%
14	1%	2%	1%	1%	1%	2%	2%	1%	1%	1%	0%
15	1%	2%	1%	1%	1%	2%	1%	1%	2%	2%	1%
16	1%	1%	0%	1%	1%	2%	1%	0%	1%	1%	1%
17	1%	1%	1%	1%	1%	1%	1%	1%	2%	1%	1%
18	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	0%
19	1%	1%	1%	1%	0%	0%	1%	1%	1%	1%	0%
20	0%	1%	1%	0%	0%	0%	0%	0%	1%	1%	0%
21	1%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%
22	0%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%
23	0%	1%	0%	0%	1%	1%	0%	0%	0%	0%	0%
24 or more	5%	4%	2%	1%	2%	2%	3%	1%	4%	3%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
6 or more	33%	35%	23%	27%	27%	33%	36%	30%	39%	30%	22%

Source: Clark, D., Evans, J., "Analysis of Hourly Surface Weather Observations, 1988-1992," computer data file, MIT/Lincoln Laboratory, Lexington, MA (1995)

Appendix G -- Airport Annual Traffic and Aircraft Operating Cost Profiles

Aircraft Operating Cost (1996 $) Profile by User Class

	Hourly Aircraft Operating Cost[1] (1996 $/hour)							Aircraft Operating Cost (1996 $/minute)	
				Fuel & Oil					
	Crew	Maint	Subtot	Airborne	Ground[2]	Dep	Arr	Dep	Arr
Sched'd Commercial Service	950	653	1603	776	259	1862	2379	31.03	39.65
Air Carrier w/o Commuters	1125	749	1874	921	307	2181	2795	36.35	46.58
Commuter only	180	234	414	142	47	461	556	7.69	9.27
Non-sched'd com'l	121	182	303	109	36	339	412	5.66	6.87
General Aviation	na	107	107	75	25	132	182	2.20	3.03
Military[3]	-	-	800	800	267	1067	1600	17.78	26.67

1. Source: Federal Aviation Administration, "Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Programs," Final Report FAA-APO-98-8, Office of Aviation Policy and Plans, Washington, DC 20591 (June 1998)
2. Ground fuel and oil cost is assumed to be 1/3 of airborne cost
3. Military costs are estimated by equally distributing total cost between Crew and Maintenance versus Airborne Fuel and Oil

Aircraft Operating Cost (1996 $) Summary by Arrival and Departure

	Aircraft Operating Cost Rate (1996 $/minute)					
	Itinerant Air Carrier	Itinerant Commuter	Itinerant Gen Av	Itinerant Military	Local Gen Av	Local Military
Departure	36.35	7.69	2.20	17.78	2.20	17.78
Arrival	46.58	9.27	3.03	26.67	3.03	26.67

1996 Annual Operations and Average Aircraft Operation Cost Profile by Airport[1,2]

		Distribution of Annual Operations (percent)							Ave Aircraft Op Cost[3] (1996 $/min)	
Airport	Year	Itinerant Air Carrier	Itinerant Commuter	Itinerant Gen Av	Itinerant Military	Local Gen Av	Local Military	Annual Operations	Departure	Arrival
ATL - Atlanta	1996	76.7%	20.0%	3.0%	0.4%	0.0%	0.0%	772597	29.54	37.75
BDL - Bradley	1996	35.3%	35.4%	23.2%	4.6%	1.4%	0.1%	160752	16.92	21.72
BNA - Nashville	1996	40.6%	30.2%	27.3%	1.9%	0.0%	0.0%	226274	18.01	23.03
BOS - Boston	1996	49.9%	43.9%	6.1%	0.1%	0.0%	0.0%	462507	21.66	27.52
BWI - Baltimore-Washington	1996	55.7%	32.5%	8.2%	0.5%	2.9%	0.1%	270156	23.11	29.48
CLE - Cleveland	1996	49.9%	38.6%	10.2%	1.0%	0.2%	0.0%	291029	21.54	27.44
CLT - Charlotte	1996	58.8%	27.3%	13.1%	0.8%	0.0%	0.0%	457054	23.89	30.51
COS - Colorado Springs	1996	25.0%	4.6%	23.3%	8.0%	33.4%	5.7%	227201	13.14	17.47
CVG - Cincinnati	1996	47.3%	48.6%	3.7%	0.3%	0.0%	0.0%	393523	21.09	26.76
DAB - Daytona Beach	1996	3.1%	1.1%	75.4%	0.4%	19.9%	0.1%	268631	3.40	4.58
DCA - Washington National	1996	56.9%	25.9%	15.7%	1.6%	0.0%	0.0%	309754	23.30	29.81
DEN - Denver	1996	70.5%	24.1%	5.2%	0.2%	0.0%	0.0%	454234	27.63	35.28
DFW - Dallas-Ft. Worth	1996	70.4%	26.3%	3.2%	0.1%	0.0%	0.0%	869831	27.70	35.36
DTW - Detroit	1996	65.8%	18.9%	15.0%	0.3%	0.0%	0.0%	531098	25.76	32.95
EWR - Newark	1996	70.5%	25.1%	4.3%	0.0%	0.0%	0.0%	443431	27.66	35.31
FLL - Ft. Lauderdale	1996	42.4%	25.8%	30.7%	0.3%	0.8%	0.0%	236342	18.14	23.17
HOU - Houston Hobby	1996	46.9%	7.7%	45.2%	0.0%	0.2%	0.0%	252254	18.64	23.94
HPN - Westchester Co.	1996	5.8%	18.3%	55.5%	0.2%	20.3%	0.0%	192717	5.21	6.74
IAD - Washington Dulles	1996	27.5%	53.9%	16.5%	2.1%	0.0%	0.0%	330439	14.88	18.88

IAH - Houston International	1996	74.6%	19.3%	6.0%	0.2%	0.0%	0.0%	391939	28.74	36.74
JFK - N.Y. Kennedy	1996	62.9%	32.9%	4.1%	0.1%	0.0%	0.0%	360511	25.49	32.49
LAS - Las Vegas	1996	57.3%	16.0%	19.4%	3.9%	3.4%	0.0%	479625	23.26	29.92
LAX - Los Angeles	1996	65.2%	31.1%	3.3%	0.4%	0.0%	0.0%	764002	26.23	33.45
LGA - N.Y. LaGuardia	1996	70.4%	23.7%	5.8%	0.1%	0.0%	0.0%	342618	27.55	35.18
LGB - Long Beach	1996	1.7%	1.0%	51.9%	0.3%	45.1%	0.0%	481937	2.88	3.91
MCO - Orlando	1996	56.9%	32.9%	8.6%	1.5%	0.0%	0.0%	341942	23.70	30.25
MDW - Chicago Midway	1996	49.6%	19.0%	30.3%	0.9%	0.2%	0.0%	254351	20.31	26.02
MEM - Memphis	1996	53.1%	28.4%	16.7%	1.6%	0.1%	0.0%	363945	22.14	28.31
MIA - Miami	1996	57.6%	29.5%	11.8%	1.1%	0.0%	0.0%	546487	23.65	30.21
MSP - Minneapolis	1996	62.8%	25.2%	10.7%	0.6%	0.6%	0.0%	483570	25.13	32.10
OAK - Oakland	1996	32.8%	12.5%	32.2%	0.2%	22.2%	0.1%	516498	14.14	18.18
ORD - Chicago O'Hare	1996	82.6%	13.2%	3.9%	0.3%	0.0%	0.0%	909186	31.18	39.90
PDX - Portland	1996	39.2%	41.6%	14.1%	3.3%	1.6%	0.1%	305964	18.40	23.50
PHL - Philadelphia	1996	53.5%	33.7%	11.6%	1.2%	0.0%	0.0%	406121	22.52	28.73
PHX - Phoenix	1996	65.0%	16.0%	16.5%	1.2%	1.2%	0.0%	544363	25.48	32.64
PIT - Pittsburgh	1996	57.7%	34.1%	6.1%	2.1%	0.0%	0.0%	447436	24.11	30.79
SAN - San Diego	1996	63.6%	26.2%	7.7%	2.5%	0.0%	0.0%	243595	25.76	32.96
SDF - Louisville	1996	57.9%	19.9%	19.3%	2.5%	0.3%	0.0%	173152	23.46	30.09
SEA - Seattle	1996	60.0%	38.0%	1.9%	0.1%	0.0%	0.0%	397591	24.78	31.54
SFO - San Francisco	1996	72.9%	17.5%	6.0%	0.5%	3.0%	0.0%	442281	28.14	36.00
SLC - Salt Lake City	1996	52.5%	24.3%	21.9%	1.2%	0.1%	0.0%	373815	21.65	27.69
STL - St. Louis	1996	69.7%	22.5%	6.6%	1.2%	0.0%	0.0%	517352	27.43	35.08
TEB - Teterboro	1996	0.1%	13.2%	84.3%	0.1%	2.2%	0.0%	193260	2.97	3.92

2015 Annual Operations and Average Aircraft Operation Cost Profile by Airport[1,2]

		Distribution of Annual Operations (percent)							Ave Aircraft Op Cost[3] (1996 $/min)	
Airport	Year	Itinerant Air Carrier	Itinerant Commuter	Itinerant Gen Av	Itinerant Military	Local Gen Av	Local Military	Annual Operations	Departure	Arrival
ATL - Atlanta	2015	79.9%	17.9%	1.8%	0.3%	0.0%	0.0%	1024514	30.53	39.03
BDL - Bradley	2015	40.5%	38.5%	16.4%	3.4%	1.1%	0.1%	215164	18.70	23.91
BNA - Nashville	2015	48.9%	32.0%	17.7%	1.5%	0.0%	0.0%	287594	20.87	26.66
BOS - Boston	2015	51.7%	43.9%	4.3%	0.1%	0.0%	0.0%	540545	22.28	28.31
BWI - Baltimore-Washington	2015	63.6%	29.5%	4.5%	0.3%	2.0%	0.1%	405144	25.61	32.68
CLE - Cleveland	2015	48.7%	44.9%	5.6%	0.7%	0.2%	0.0%	437960	21.39	27.19
CLT - Charlotte	2015	59.5%	32.2%	7.7%	0.6%	0.0%	0.0%	642941	24.39	31.10
COS - Colorado Springs	2015	33.0%	6.0%	24.2%	5.8%	26.9%	4.2%	313580	15.34	20.12
CVG - Cincinnati	2015	47.8%	50.5%	1.5%	0.2%	0.0%	0.0%	774632	21.32	27.03
DAB - Daytona Beach	2015	2.8%	1.0%	80.7%	0.4%	15.1%	0.1%	309444	3.27	4.41
DCA - Washington National	2015	57.4%	28.0%	13.2%	1.5%	0.0%	0.0%	332173	23.57	30.13
DEN - Denver	2015	70.3%	26.5%	3.1%	0.1%	0.0%	0.0%	625807	27.67	35.32
DFW - Dallas-Ft. Worth	2015	67.2%	30.9%	1.9%	0.1%	0.0%	0.0%	1500178	26.85	34.23
DTW - Detroit	2015	72.5%	17.2%	10.1%	0.2%	0.0%	0.0%	839916	27.92	35.71
EWR - Newark	2015	70.0%	27.5%	2.5%	0.0%	0.0%	0.0%	643228	27.62	35.24
FLL - Ft. Lauderdale	2015	58.1%	19.4%	21.8%	0.2%	0.5%	0.0%	355807	23.13	29.59
HOU - Houston Hobby	2015	51.4%	12.0%	36.4%	0.0%	0.2%	0.0%	312815	20.41	26.16
HPN - Westchester Co.	2015	9.9%	26.9%	43.6%	0.2%	19.4%	0.0%	201543	7.09	9.07
IAD - Washington Dulles	2015	31.6%	54.9%	11.9%	1.5%	0.0%	0.0%	456618	16.25	20.58
IAH - Houston International	2015	75.3%	21.8%	2.8%	0.1%	0.0%	0.0%	694148	29.14	37.22
JFK - N.Y. Kennedy	2015	65.7%	31.6%	2.5%	0.1%	0.0%	0.0%	425021	26.40	33.66
LAS - Las Vegas	2015	71.3%	12.9%	11.5%	2.3%	2.0%	0.0%	811961	27.62	35.44
LAX - Los Angeles	2015	70.0%	28.0%	1.6%	0.3%	0.0%	0.0%	1086801	27.71	35.36
LGA - N.Y. LaGuardia	2015	74.9%	21.7%	3.2%	0.1%	0.0%	0.0%	408173	29.00	37.04
LGB - Long Beach	2015	3.2%	1.0%	57.1%	0.3%	38.4%	0.0%	565796	3.39	4.56
MCO - Orlando	2015	67.5%	27.0%	4.6%	0.8%	0.0%	0.0%	631412	26.88	34.33
MDW - Chicago Midway	2015	57.5%	18.3%	23.3%	0.7%	0.3%	0.0%	331228	22.94	29.37
MEM - Memphis	2015	58.8%	27.2%	12.9%	1.0%	0.1%	0.0%	557692	23.93	30.57
MIA - Miami	2015	66.8%	25.9%	6.5%	0.8%	0.0%	0.0%	817434	26.56	33.93

MSP - Minneapolis	2015	68.1%	23.4%	7.7%	0.4%	0.4%	0.0%	721519	26.82	34.26
OAK - Oakland	2015	45.9%	10.3%	32.0%	0.1%	11.6%	0.1%	637764	18.46	23.70
ORD - Chicago O'Hare	2015	81.8%	15.3%	2.6%	0.2%	0.0%	0.0%	1146816	31.01	39.67
PDX - Portland	2015	45.9%	43.4%	7.4%	2.2%	1.1%	0.1%	468065	20.61	26.26
PHL - Philadelphia	2015	60.5%	33.3%	5.4%	0.8%	0.0%	0.0%	582848	24.82	31.65
PHX - Phoenix	2015	73.7%	15.8%	8.9%	0.8%	0.8%	0.0%	833330	28.36	36.31
PIT - Pittsburgh	2015	51.8%	41.5%	5.2%	1.5%	0.0%	0.0%	616968	22.40	28.53
SAN - San Diego	2015	69.2%	25.8%	3.4%	1.6%	0.0%	0.0%	367478	27.50	35.16
SDF - Louisville	2015	64.8%	19.7%	13.5%	1.8%	0.2%	0.0%	247962	25.68	32.89
SEA - Seattle	2015	67.7%	31.0%	1.3%	0.0%	0.0%	0.0%	580991	27.01	34.44
SFO - San Francisco	2015	78.1%	15.6%	3.9%	0.4%	2.0%	0.0%	676707	29.80	38.12
SLC - Salt Lake City	2015	60.4%	24.8%	14.0%	0.7%	0.1%	0.0%	584571	24.30	31.05
STL - St. Louis	2015	73.4%	21.9%	3.8%	0.8%	0.0%	0.0%	733886	28.61	36.57
TEB - Teterboro	2015	0.1%	13.2%	84.3%	0.1%	2.2%	0.0%	193260	2.97	3.92

1. Source for 1996 annual operations data: Federal Aviation Administration, "1997 Terminal Area Forecast (TAF) System," Office of Aviation Policy and Plans, Washington, DC 20591, FAA APO Home Page, Internet WWW Site (Oct 1998); 2015 annual operations data are linear extrapolations of 1996-2010 data.
2.Aircraft operating cost data based on: Federal Aviation Administration, "Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Programs," Final Report FAA-APO-98-8, Office of Aviation Policy and Plans, Washington, DC 20591 (June 1998)
3. Average Aircraft Operating Cost data are weighted according user class traffic distribution for each airport

CODAS 1997 Delay Summary and Rank by Non-Study Site Airport[1]

	Total Delay (units not specified)			1/7th Percentile Delay Affinity
Non-study Site	Taxi Out	Airborne	Total	Group Rank
ATL	6.3	6.67	12.97	1
STL	6.96	2.96	9.92	1
CVG	4.63	4.60	9.23	1
BOS	4.26	4.41	8.67	1
DTW	5.85	2.82	8.67	1
CLT	3.96	4.28	8.24	2
SLC	4.06	4.10	8.16	2
MIA	4.66	2.80	7.46	2
PIT	3.29	4.15	7.44	2
IAH	4.48	2.66	7.14	2
CLE	3.73	3.33	7.06	3
DCA	4.08	2.09	6.17	3
MEM	3.88	2.12	6.00	3
SEA	2.63	3.29	5.92	3
PHX	3.64	1.48	5.12	3
FLL	2.16	2.42	4.58	4
MCO	2.18	2.21	4.39	4
LAS	3.44	0.93	4.37	4
HOU	1.87	2.32	4.19	4
SDF	1.83	2.32	4.15	4
PDX	1.85	2.15	4.00	5
IAD	2.55	1.30	3.85	5
BDL	2.06	1.78	3.84	5
OAK	1.8	1.84	3.64	5
BWI	1.93	1.61	3.54	5
BNA	1.89	1.52	3.41	6
COS	2.14	1.26	3.40	6
SAN	2.29	1.00	3.29	6
MDW	1.82	1.26	3.08	6
DAB	na	na	na	7
HPN	na	na	na	7
LGB	na	na	na	7
TEB	na	na	na	7

1. Source: "Consolidated Operations and Delay Analysis System (CODAS)," Office of Aviation Policy and Plans, Washington, DC 20591, FAA APO Home Page, Internet WWW Site (Oct 1998);
2. Rank value identifies the delay ordering group among study site or non-study site airports.
   eg: Rank = 1 identifies the group containing one-seventh (14.3%) of the airports with the most delay
   eg: Rank = 2 identifies the group containing one-seventh (14.3%) of the airports with the second-most delay

CODAS 1997 Delay Summary by Study Site Airport[1] (provided as general information)

	Total Delay (units not specified)				Total Delay (units not specified)		
Study Site	Taxi Out	Airborne	Total	Study Site	Taxi Out	Airborne	Total
EWR	11.33	6.44	17.77	JFK	5.28	3.01	8.29
LGA	8.6	4.69	13.29	SFO	5.59	2.53	8.12
PHL	6.01	5.56	11.57	ORD	4.97	2.93	7.90
MSP	6.25	3.75	10.00	LAX	4.16	1.88	6.04
DFW	6.15	2.67	8.82	DEN	3.56	1.97	5.53

1. Source: "Consolidated Operations and Delay Analysis System (CODAS)," Office of Aviation Policy and Plans, Washington, DC 20591, FAA APO Home Page, Internet WWW Site (Oct 1998);

1996 Study Site Representative Annual Delay Savings Rank:

Sorted by unweighted average annual savings across DSTs

	1996 Total Annual Savings[1] ($ millions)				Unweighted	
Airport	TMA	pFAST	aFAST	EDP	Average	1996 Rank
1996						
ORD	15.32	42.47	61.55	96.91	54.07	na
SFO	16.78	13.33	32.44	56.84	29.85	na
LAX	13.50	8.19	10.80	31.64	16.03	1
MSP	5.83	7.30	11.89	30.32	13.83	2
EWR	5.95	3.91	4.13	12.96	6.74	3
PHL	5.98	4.12	4.85	10.90	6.46	4
DFW	10.64	0.70	1.00	12.26	6.15	5
JFK	3.72	4.09	5.87	10.08	5.94	6
LGA	8.00	1.15	1.28	9.17	4.90	na
DEN	5.48	0.41	0.76	6.83	3.37	7
total	91.21	85.66	134.57	277.92	147.34	
2015						2015 Rank
ORD	14.95	61.18	84.50	173.13	83.44	na
LAX	29.31	36.61	68.65	168.71	75.82	1
EWR	7.87	41.76	56.16	92.34	49.53	2
MSP	7.62	24.97	44.69	92.64	42.48	3
PHL	6.68	33.10	49.58	62.32	37.92	4
SFO	2.82	15.08	13.48	41.79	18.29	na
DFW	25.48	3.97	3.92	39.53	18.23	5
LGA	13.01	16.54	10.47	23.54	15.89	na
JFK	5.35	7.01	9.68	15.77	9.45	6
DEN	8.44	1.39	1.90	12.23	5.99	7
total	121.52	241.62	343.02	722.00	357.04	

1. Source: Table 9-19

Appendix H -- Background Airport Operations Data for CAP Analysis

Target Airport	1993 Air Carrier Flights[1]	1996 Air Carrier Flights[1]	2015 Air Carrier Flights[2]	1993 AAL Scheduled Flights[ref.46]	1996 Est. AAL Scheduled Flights[3]
ATL - Atlanta	236,814	296,177	409,508	9,446	11,814
BDL - Bradley	30,730	28,358	43,585	7,264	6,703
BNA - Nashville	62,754	45,923	70,273	91,365	66,860
BOS - Boston	120,957	115,301	139,695	14,611	13,928
BWI - Baltimore-Washington	60,101	75,255	128,856	7,262	9,093
CLE - Cleveland	59,625	72,681	106,536	5,914	7,209
CLT - Charlotte	121,529	134,298	191,428	4,903	5,418
COS - Colorado Springs	11,529	28,445	51,704	1,329	3,279
CVG - Cincinnati	75,763	93,151	185,061	4,255	5,232
DAB - Daytona Beach	5,390	4,180	4,295	2,083	1,615
DCA - Washington National	91,209	88,170	95,362	14,950	14,452
DEN - Denver	175,014	160,122	219,863	6,422	5,876
DFW - Dallas-Ft. Worth	295,844	306,135	503,899	229,491	237,474
DTW - Detroit	148,711	174,815	304,309	6,006	7,060
EWR - Newark	144,133	156,274	225,089	11,556	12,529
FLL - Ft. Lauderdale	42,650	50,073	103,334	3,179	3,732
HOU - Houston Hobby	61,318	59,136	80,358	4,874	4,701
HPN - Westchester Co.	4,971	5,591	10,010	610	686
IAD - Washington Dulles	44,129	45,473	72,157	6,598	6,799
IAH - Houston International	119,848	146,102	261,474	7,621	9,290
JFK - N.Y. Kennedy	104,737	113,304	139,673	42,085	45,527
LAS - Las Vegas	102,538	137,467	289,529	7,071	9,480
LAX - Los Angeles	205,801	248,896	380,629	52,097	63,006
LGA - N.Y. LaGuardia	125,613	120,532	152,954	19,110	18,337
LGB - Long Beach	12,742	4,072	9,058	1,269	406
MCO - Orlando	101,733	97,363	213,233	8,442	8,079
MDW - Chicago Midway	37,399	63,029	95,177	0	0
MEM - Memphis	86,357	96,661	163,904	3,768	4,218
MIA - Miami	154,752	157,270	273,056	88,913	90,360
MSP - Minneapolis	130,272	151,866	245,857	5,500	6,412
OAK - Oakland	60,977	84,821	146,209	1,223	1,701
ORD - Chicago O’Hare	342,324	375,534	468,968	175,636	192,675
PDX - Portland	46,601	59,936	107,441	5,018	6,454
PHL - Philadelphia	109,896	108,710	176,282	11,180	11,059
PHX - Phoenix	146,511	176,991	307,090	5,499	6,643
PIT - Pittsburgh	131,135	129,170	159,770	5,078	5,002
SAN - San Diego	67,875	77,506	127,152	12,808	14,625
SDF - Louisville	41,685	50,125	80,302	2,718	3,268
SEA - Seattle	98,978	119,211	196,546	7,191	8,661
SFO - San Francisco	143,702	161,164	264,398	15,242	17,094
SLC - Salt Lake City	85,308	98,129	176,477	3,733	4,294
STL - St. Louis	139,111	180,380	269,394	5,212	6,758
TEB - Teterboro	28	51	51	0	0
TOTAL	**4,389,094**	**4,897,838**	**7,649,946**	918,532	**1,025,002**

[1]Obtained by halving the number of air carrier operations from Reference 32

[2]Linear extrapolations from Reference 32

[3]Extrapolated from 1993 AAL Scheduled data (in Column 5) by a fixed % growth based on 1993 and 1996 actual TAF air carrier flights (in Columns 2 and 3).

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